Status of Beam-Beam Compensation with Electron Lenses in Tevatron

Vladimir Shiltsev

for the BBCompensation team:
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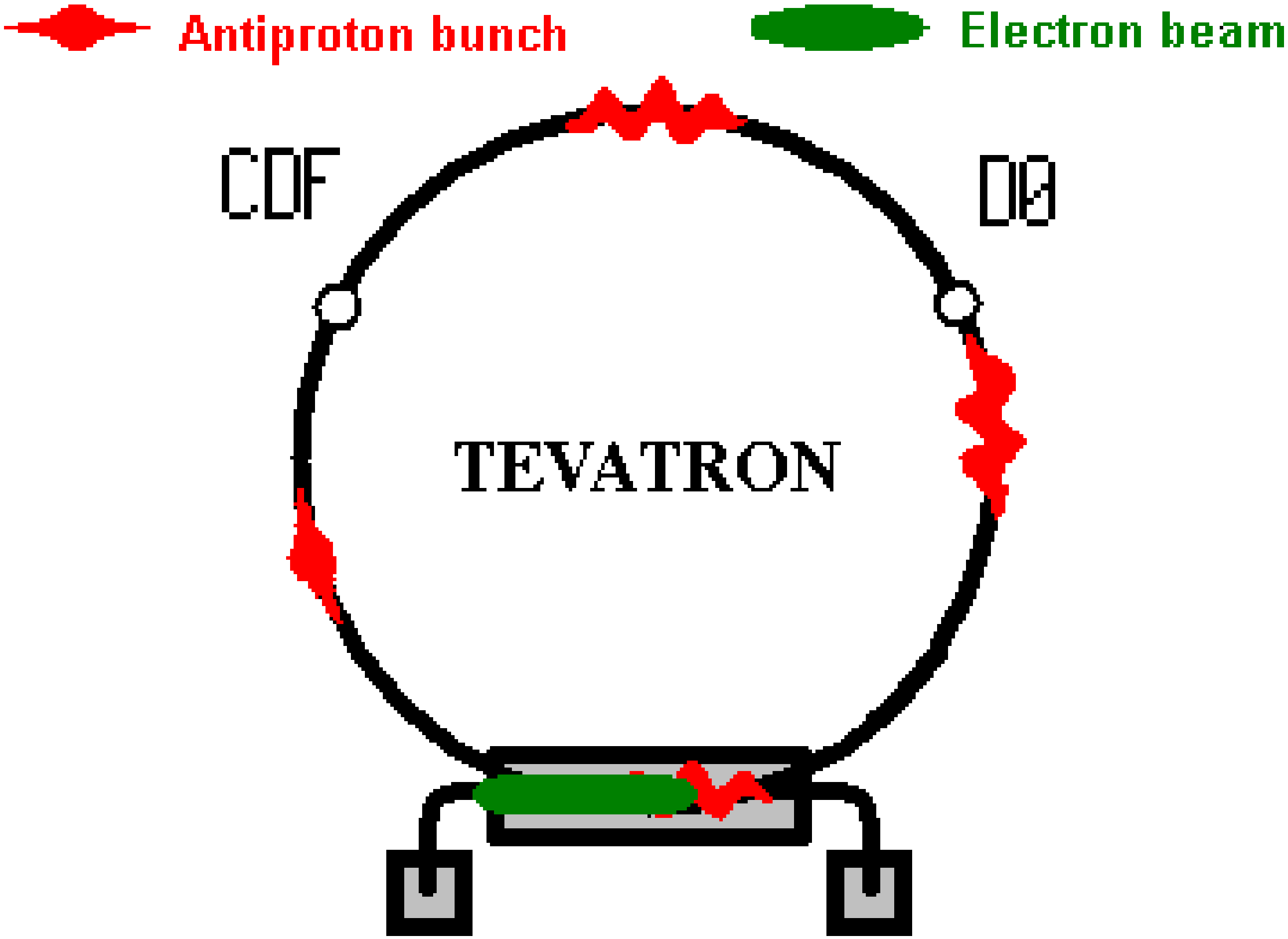
Fermilab

Content

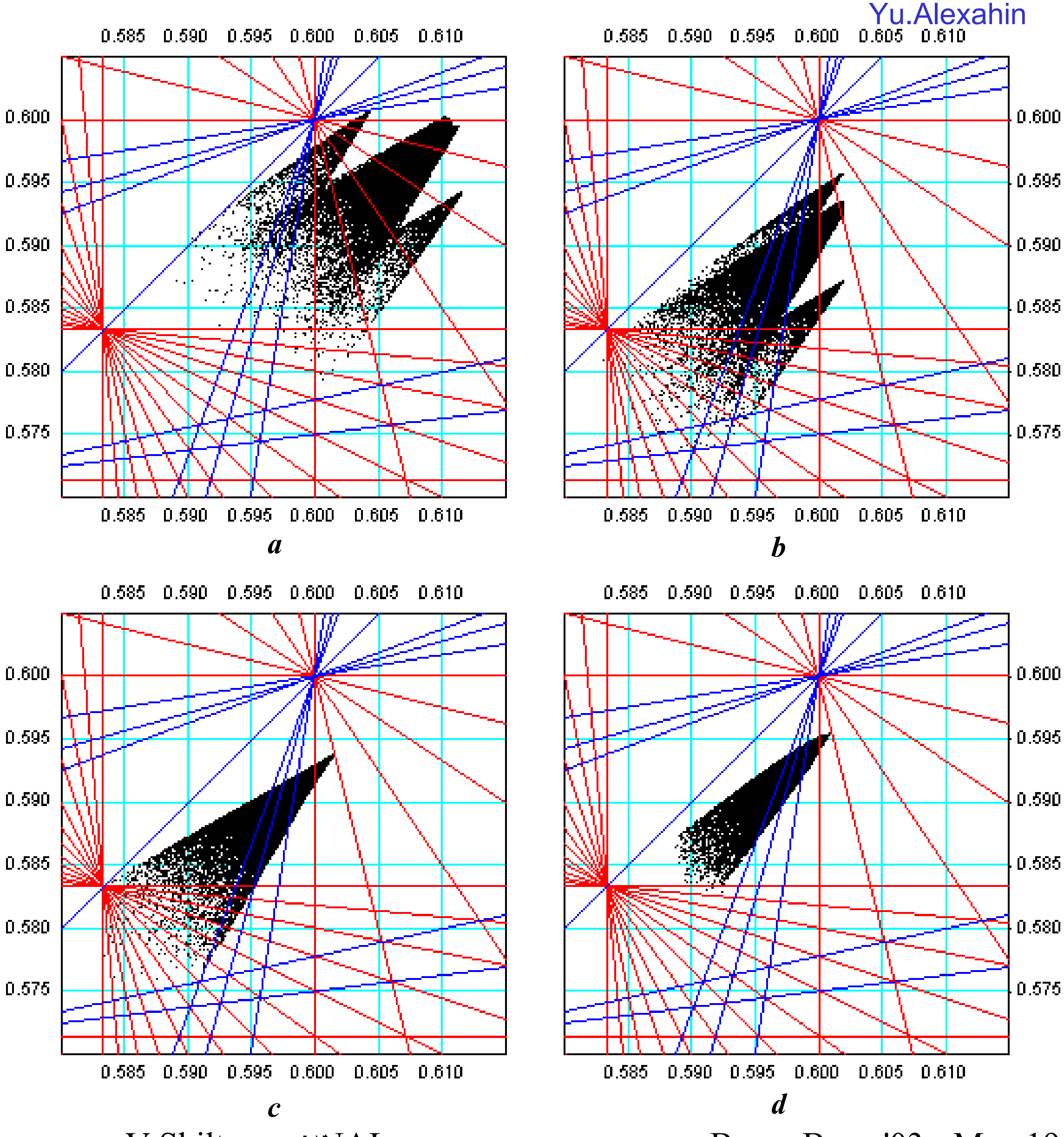
- Original idea
- Sequence of events
- TEL is good for something else
- Lifetime with TEL → improved
- First indication of successful B-B-Compensation
- What is important for the BBC?
- Next steps

Original Idea Was…



"…to compensate (in average) space charge forces of positevely charged protons acting on antiprotons in the Tevatron by interaction with a negative charge of a low energy high-current electron beam " (1997)

Compensation with Two TELs

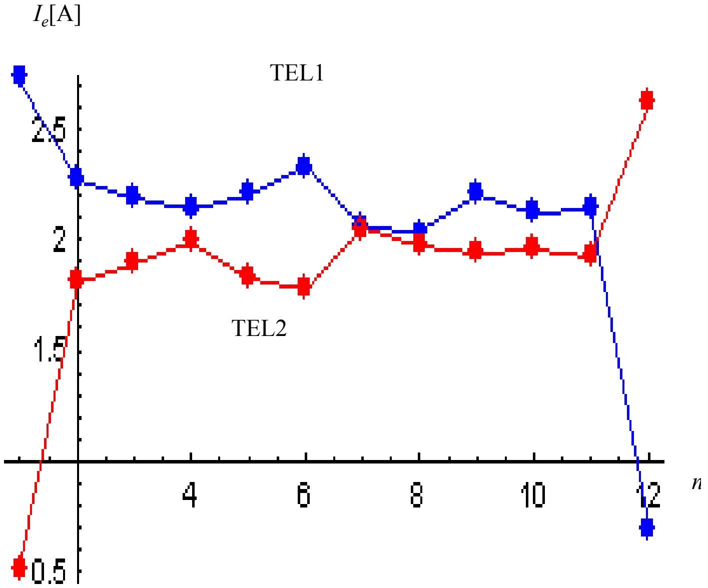


- Tev Run II: 36x36 bunches in 3 trains
- compensate beam-beam tune shifts
  - a) Run II Goal
  - b) one TEL
  - c) two TELs
  - d) 2 nonlinear TELs
- requires
  - 1-3A electron current
  - stability dJ/J<0.1%
  - e-pbar centering
  - e-beam shaping

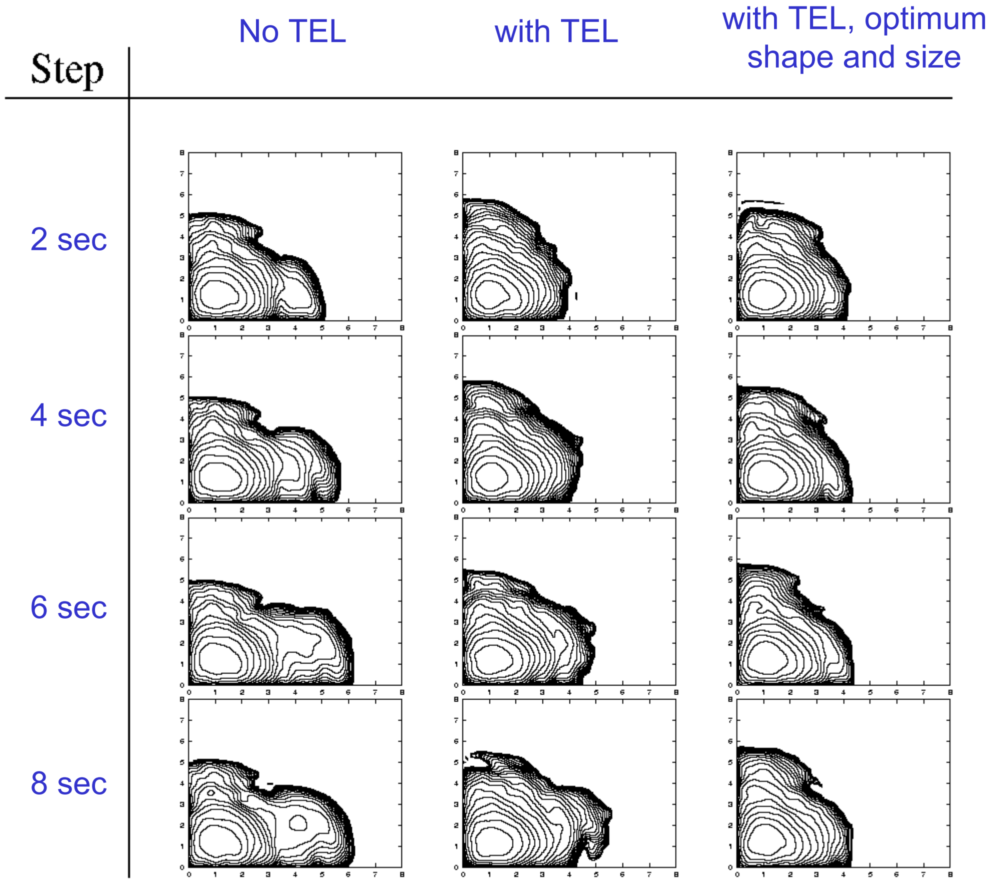
Ultimate Expectations (circa 1998-2000)

Better lifetime and smaller emittance growth of 6 out 36 bunches → ~5-10% in integrated luminosity

V.Shiltsev, Yu.Alexahin , D.Shatilov

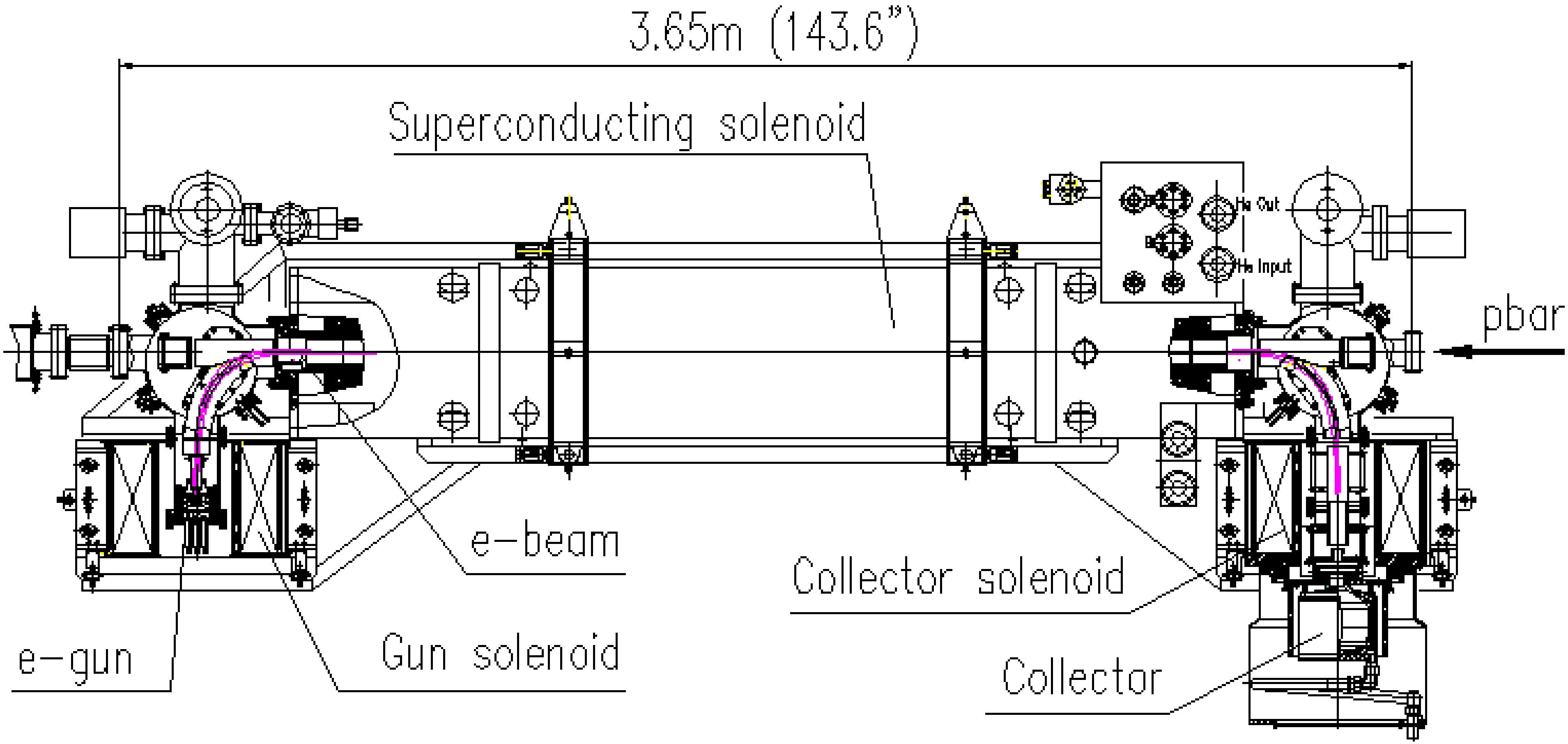


Electron currents in the two TELs as seen by different antiproton bunches #1 to #12



prototyping started in '98 →

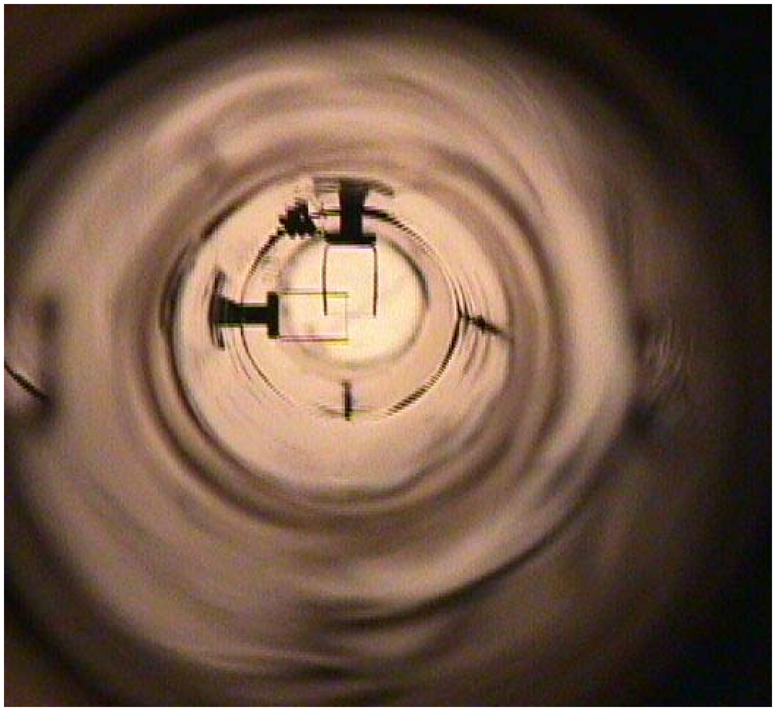
TEL-1: installed Mar.1, 2001

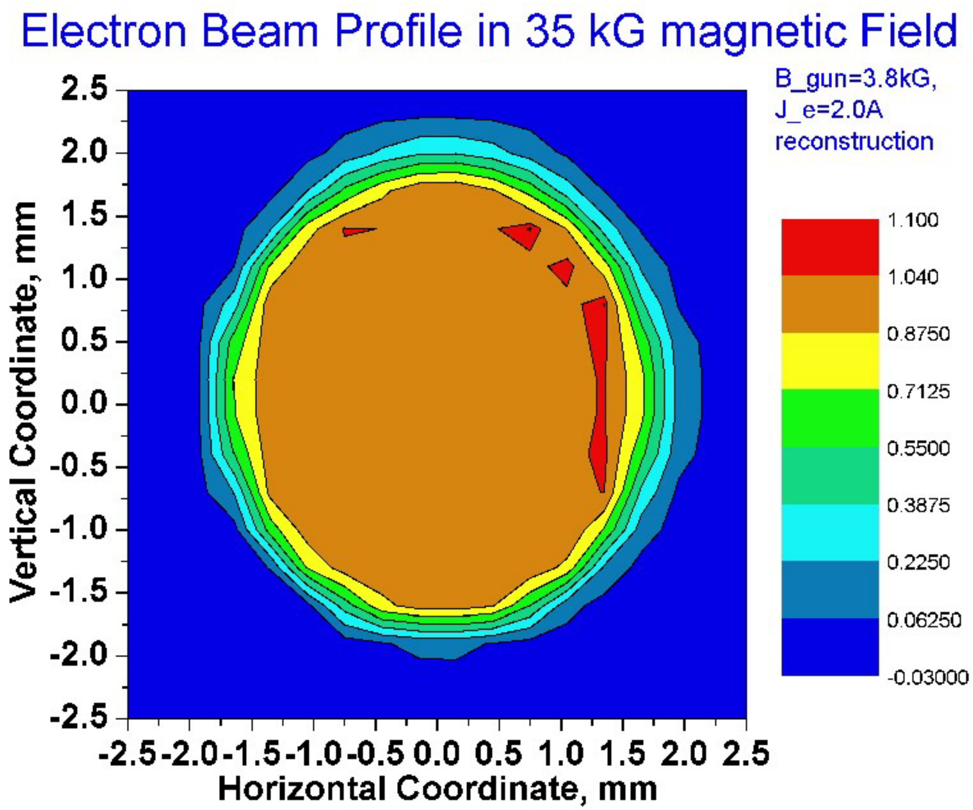


Tevatron Electron Lens in the Tevatron Tunnel, sector F48

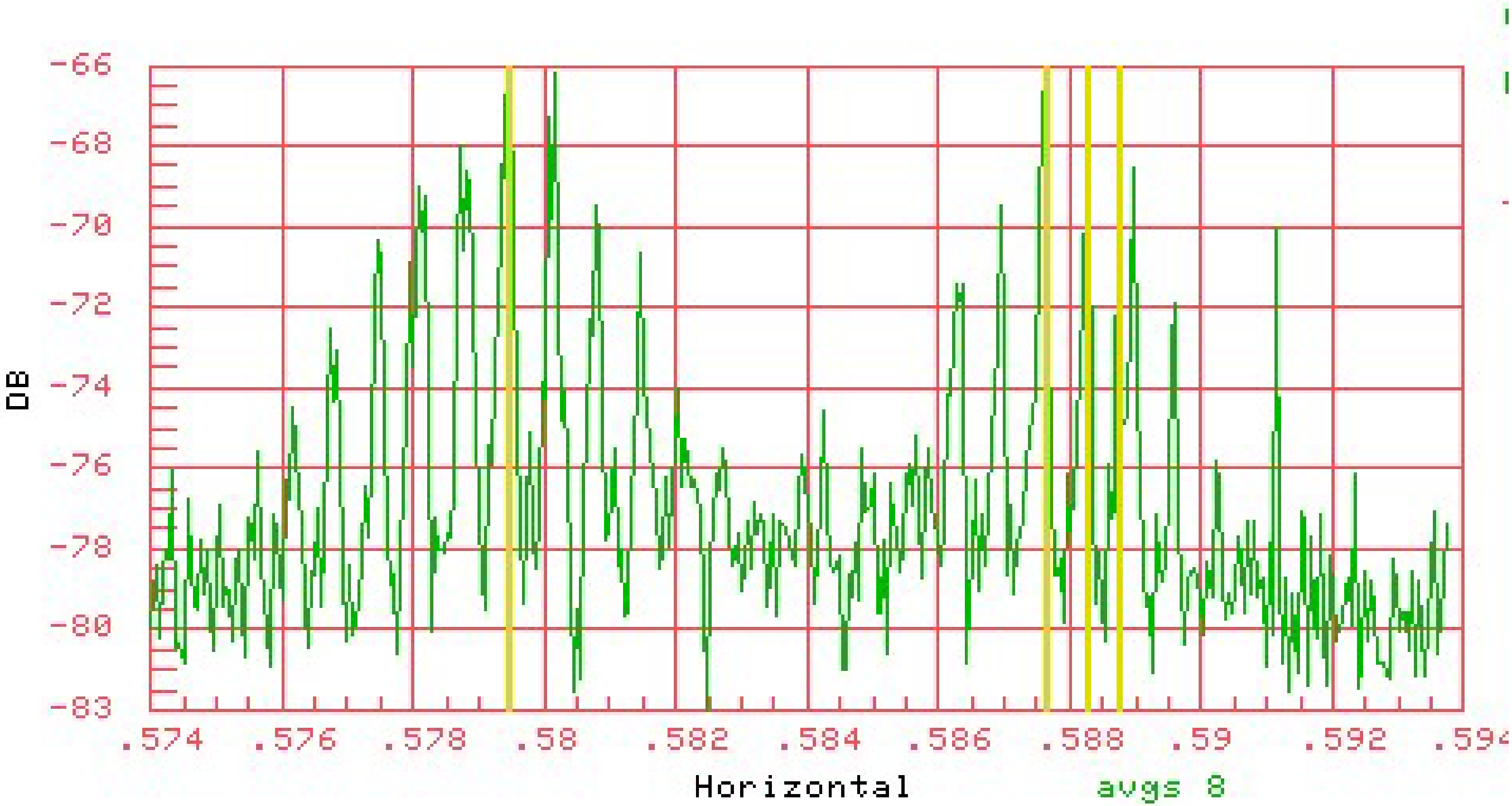
Electron Beam in Main Solenoid

- “flat” e-current density distribution +-5% over 3.4 mm diameter





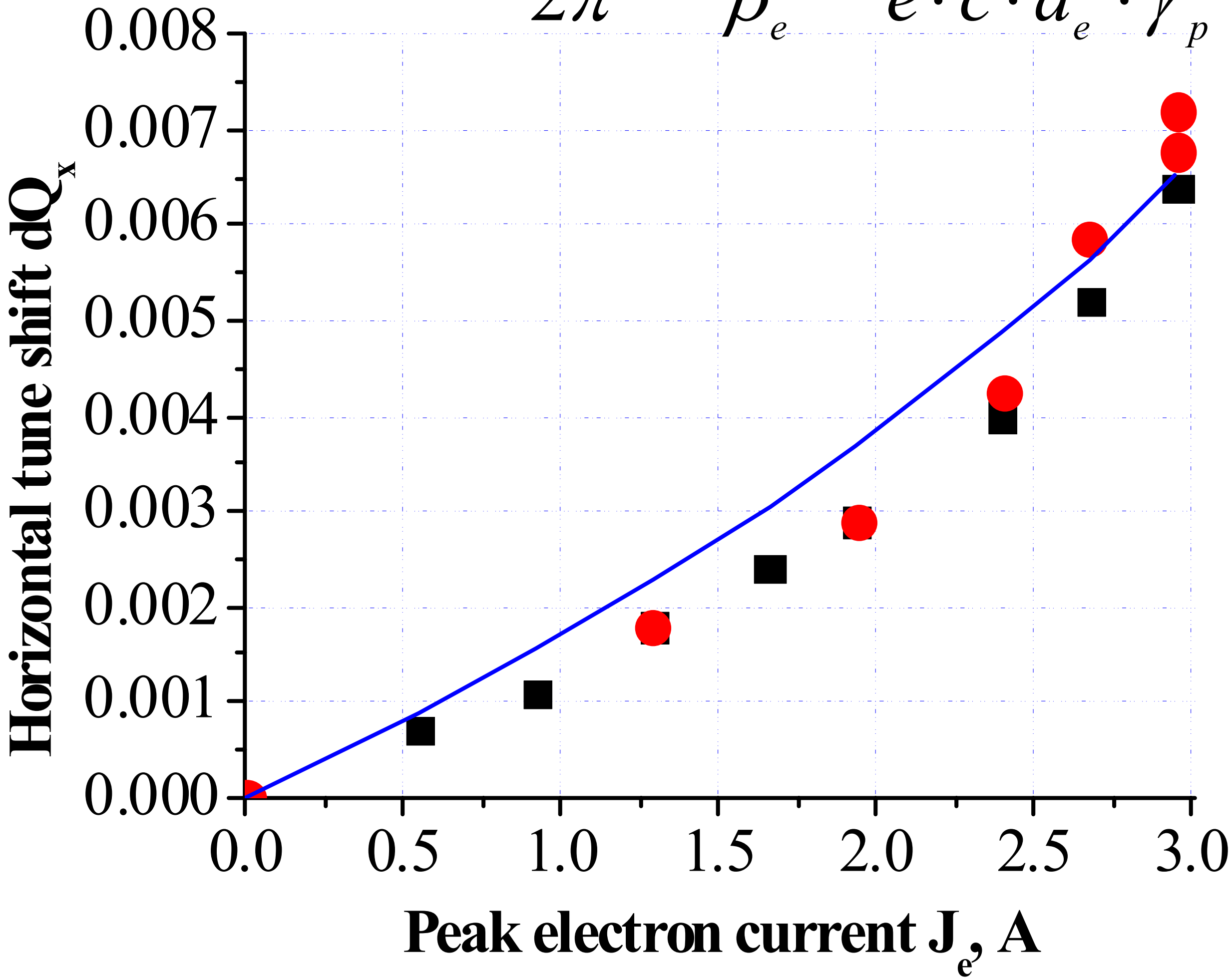
Tuneshift dQ_{hor}=+0.009 by TEL



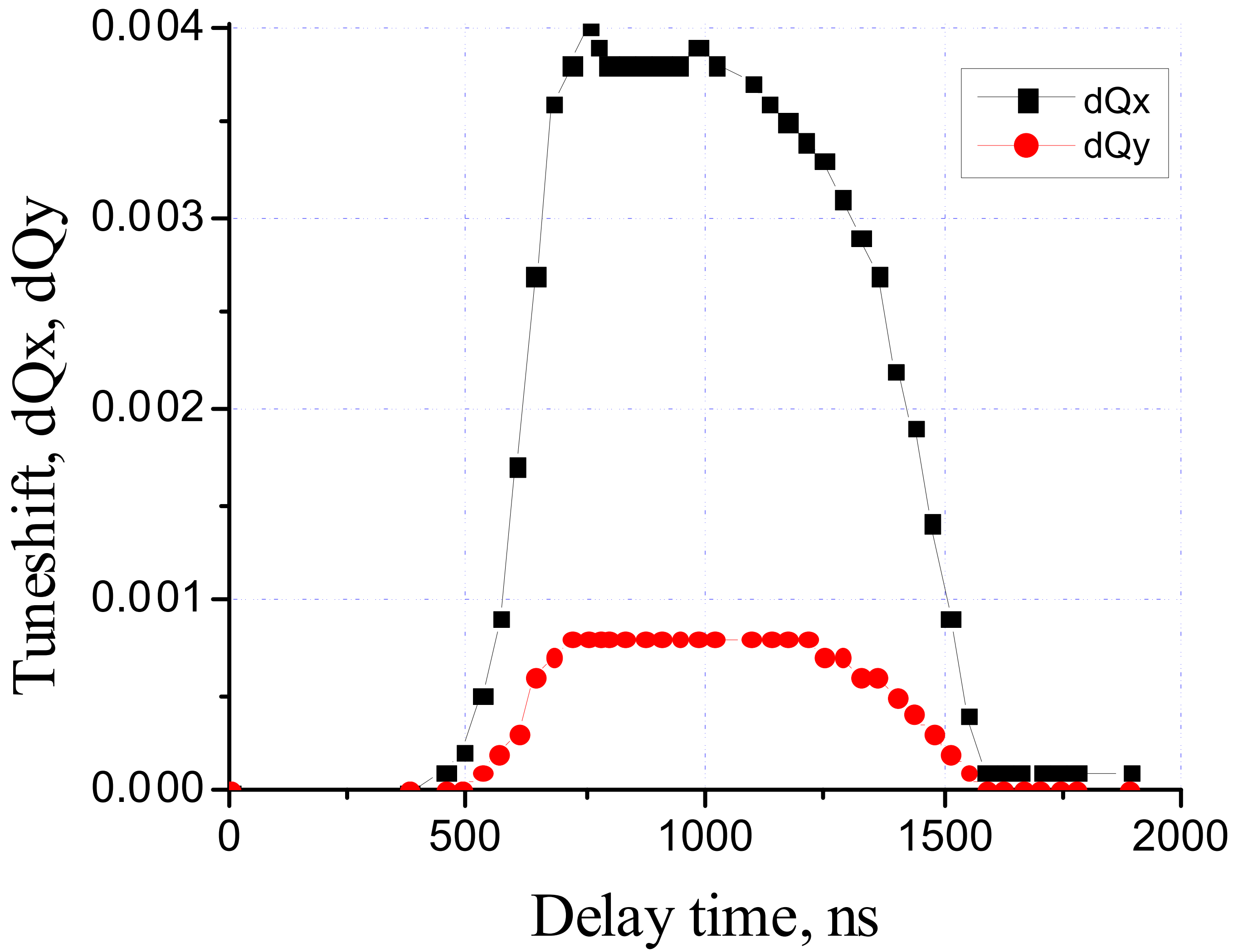
- Three bunches in the Tevatron, the TEL acts on one of them

TEL : tuneshift as predicted

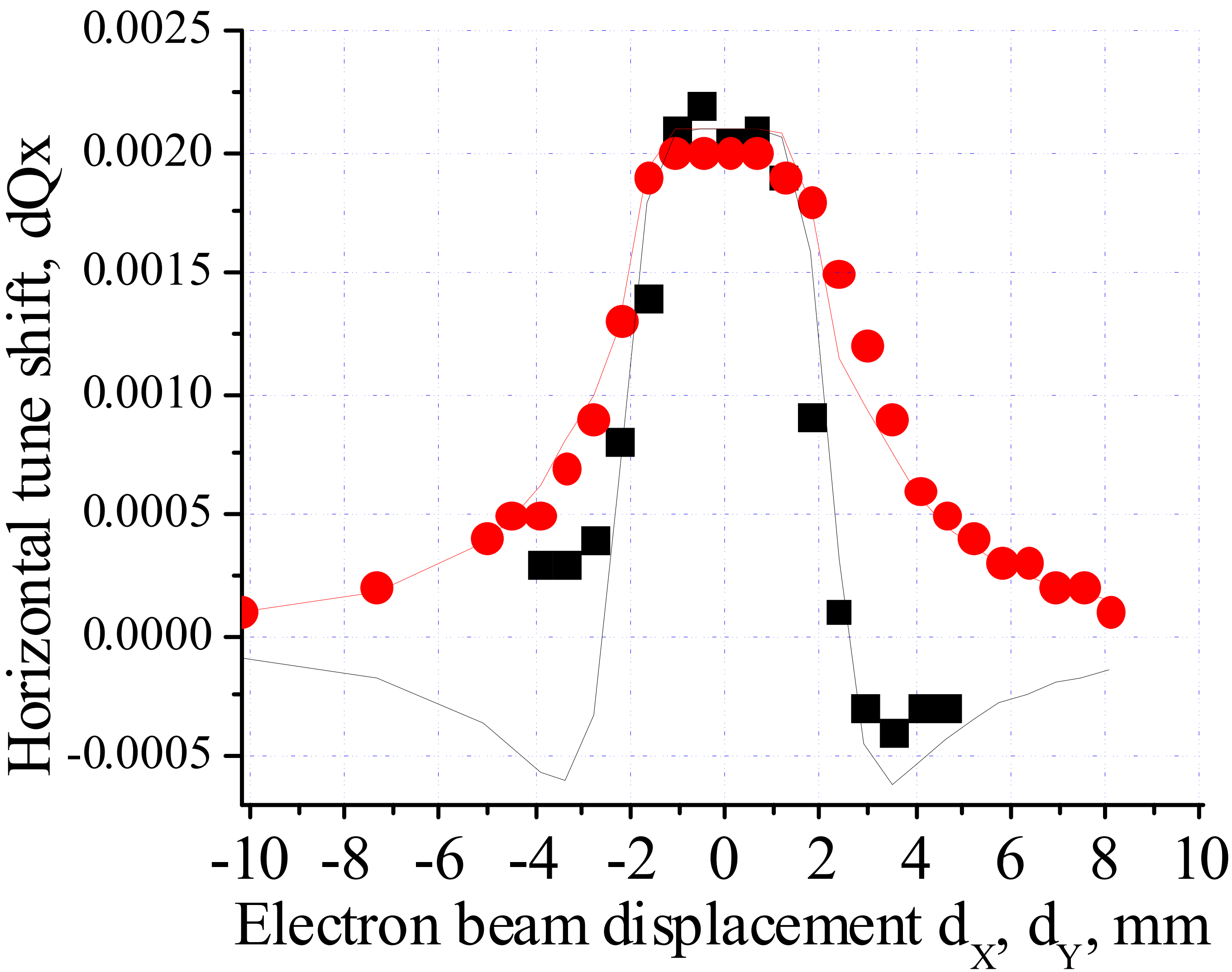
$$dQ_{x,y} = \mp \frac{\beta_{x,y}}{2\pi} \cdot \frac{1 \pm \beta_e}{\beta_e} \cdot \frac{J_e \cdot L_e \cdot r_p}{e \cdot c \cdot a_e^2 \cdot \gamma_p}$$



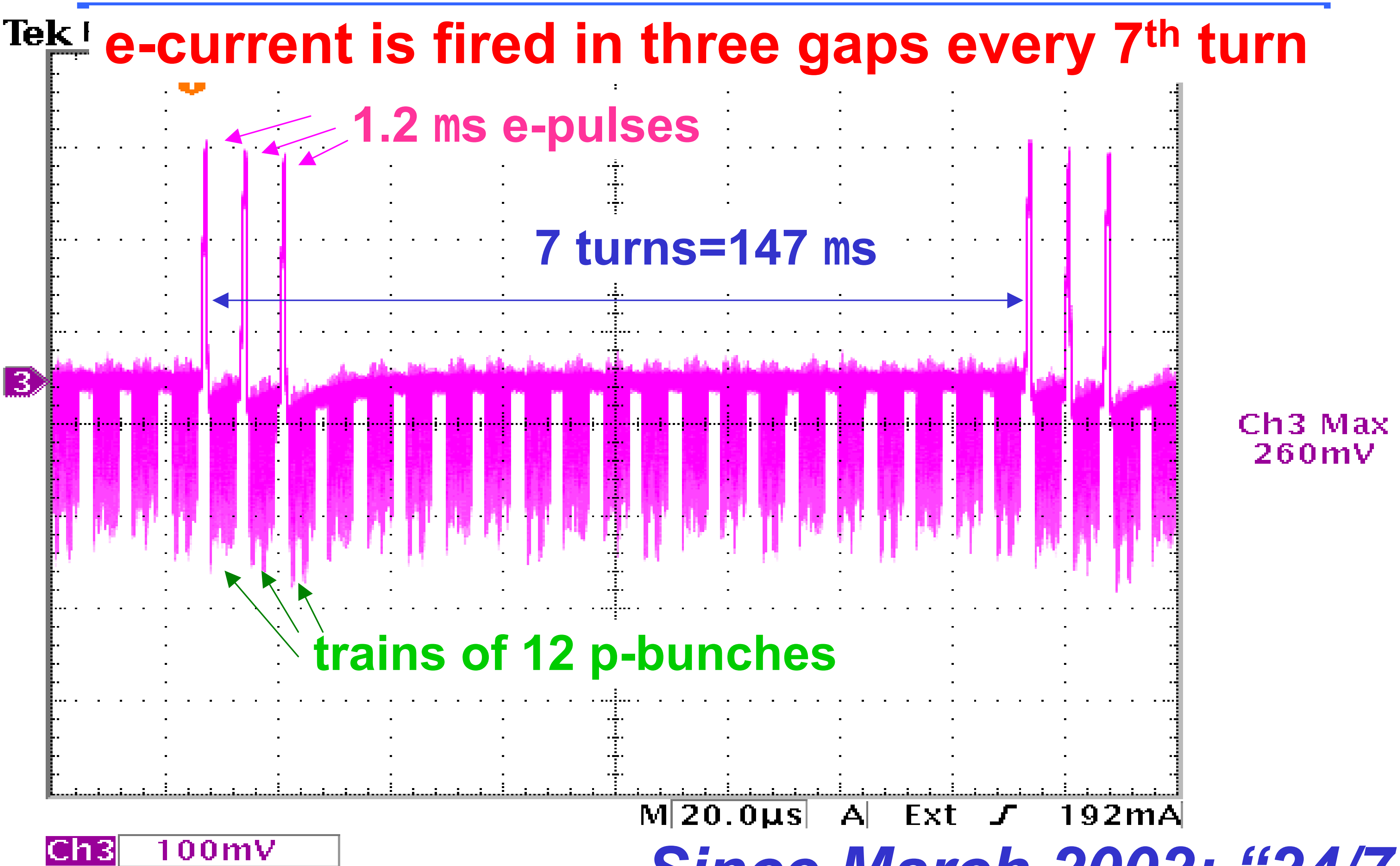
TEL : short pulses, bunch-by-bunch



TEL : tuneshift vs e-position

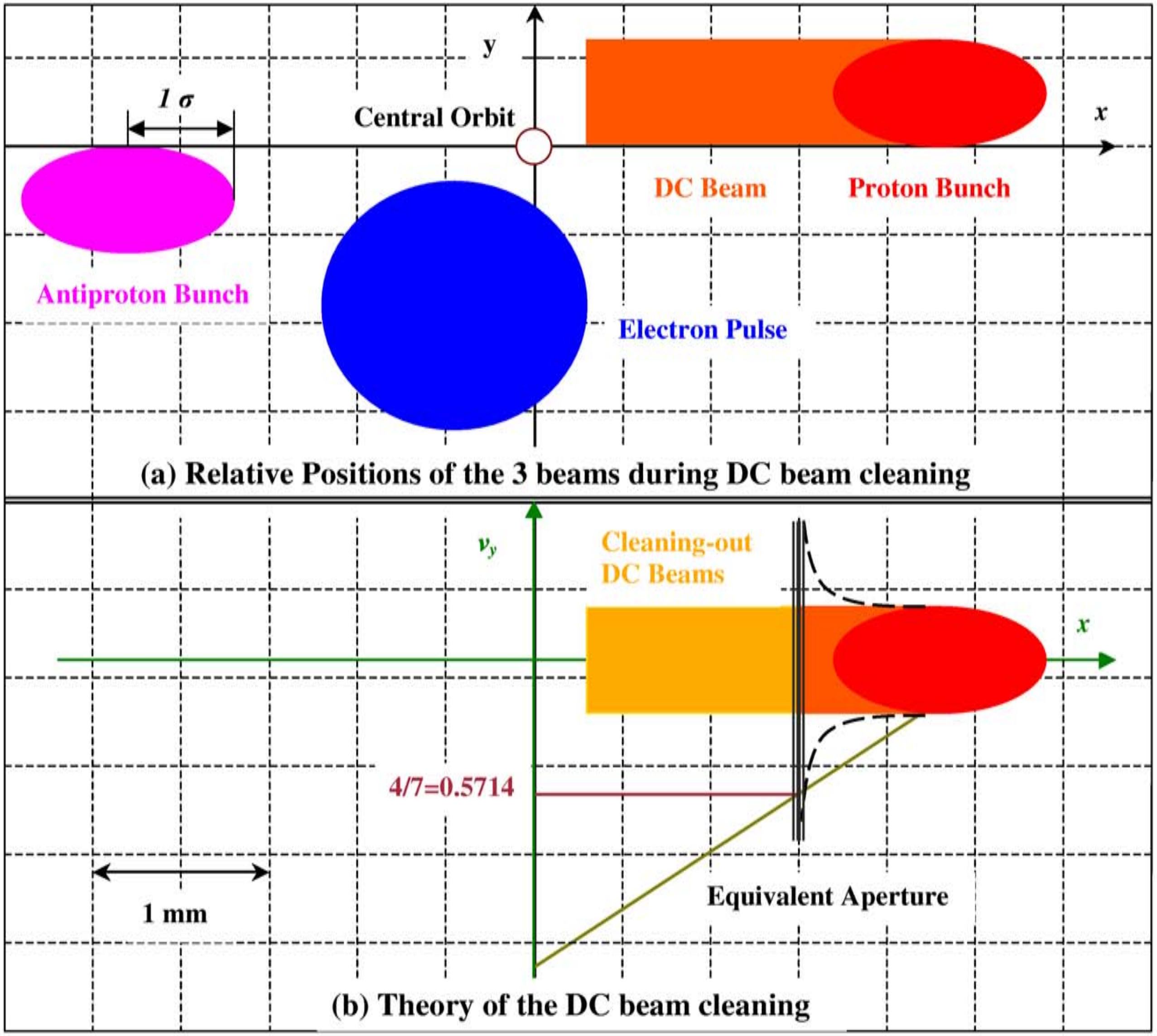


Unexpected Function: "DC Beam Killer"



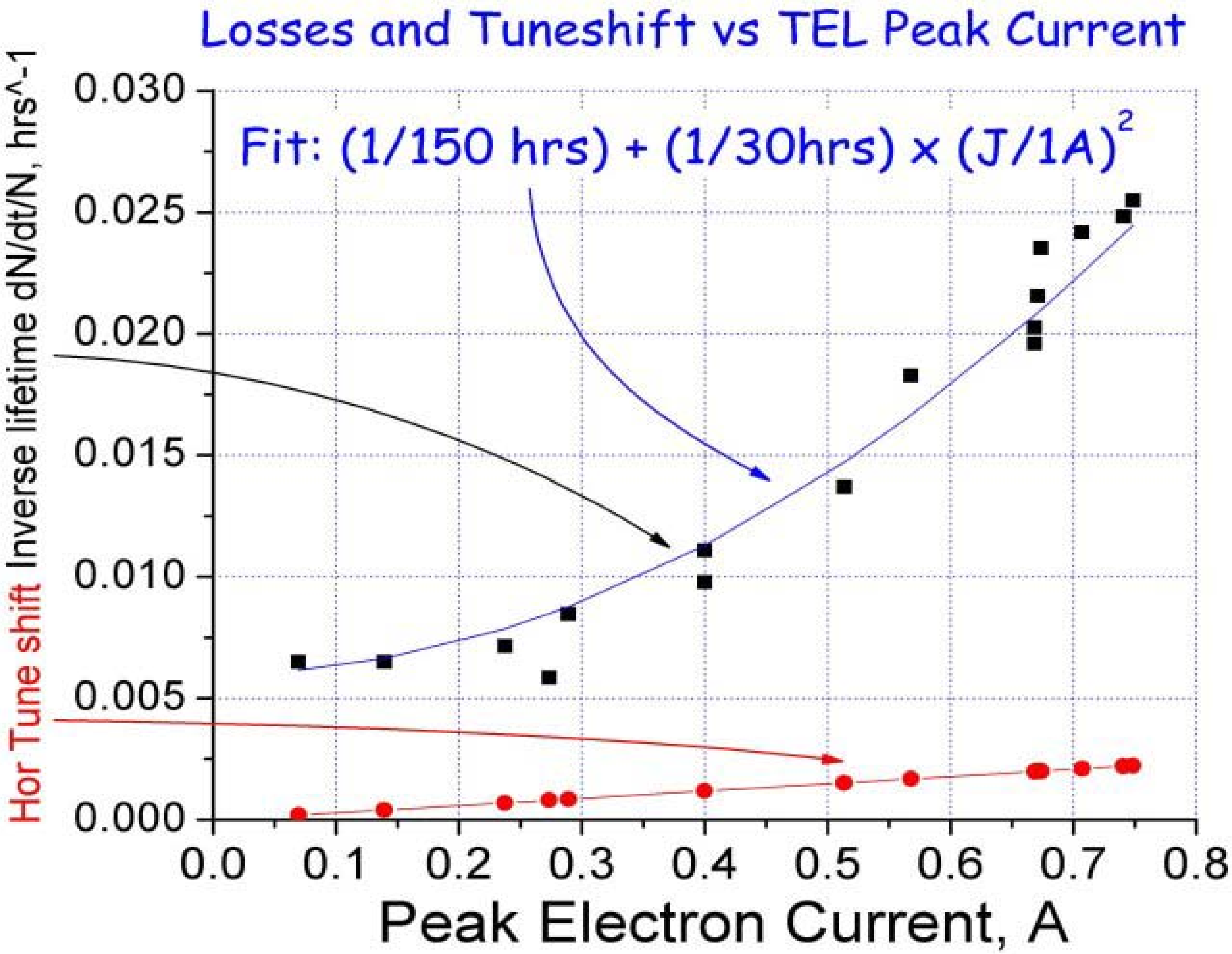
Since March 2002: "24/7"

e-Beam Position for “cleaning” vs BBC

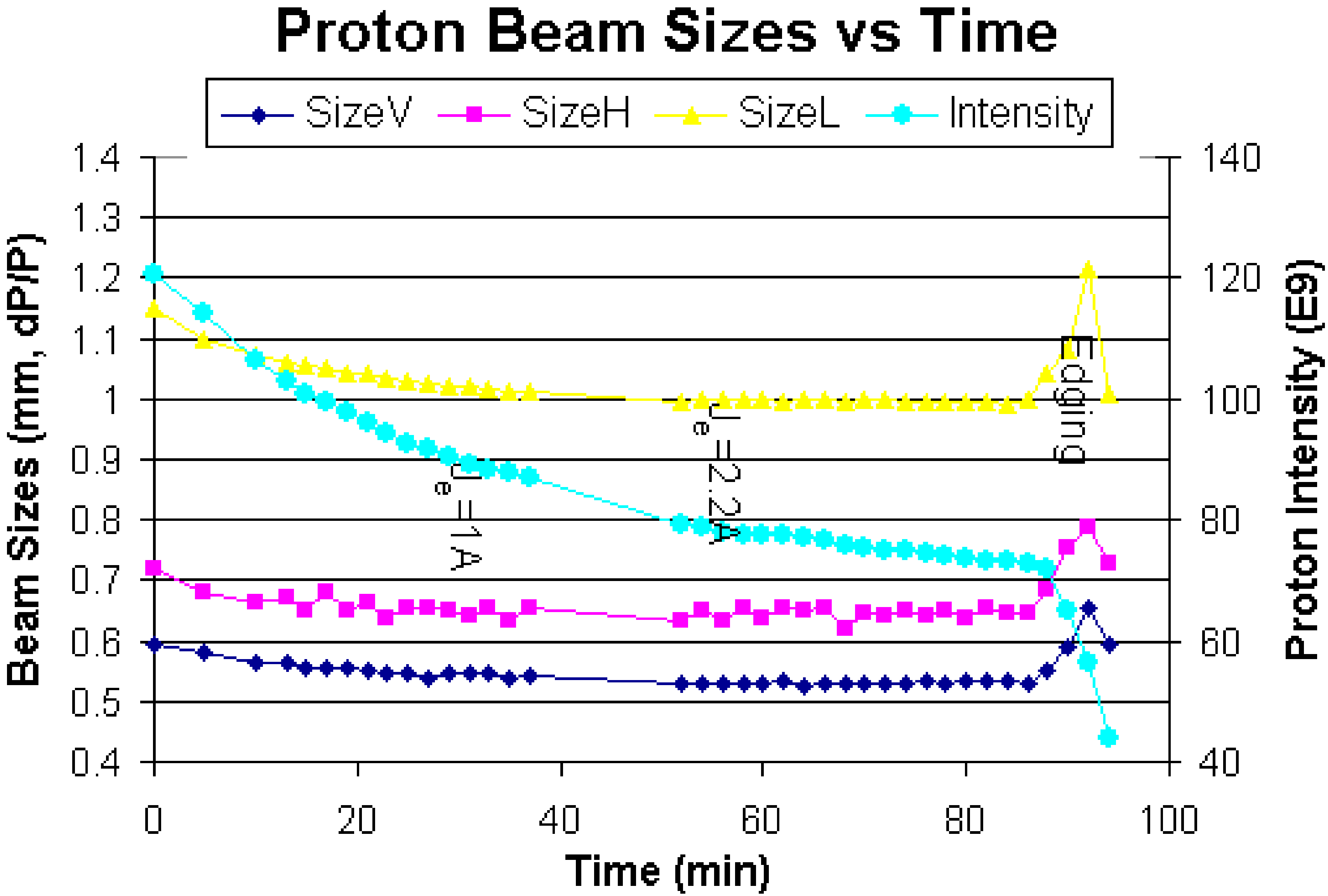


- e-beam is being moved by a set of 6 SC dipole correctors
- each corrector can move ebeam over 2¾” aperture (about 0.12Tm strength)
- intrinsic feature of the TEL is that for e-beam to be generated it needs to be able to propagate thru - the condition which requires S(correctors)=*const* in each plane, so →
- <u>moving e-beam does not affect Tev orbits !</u>

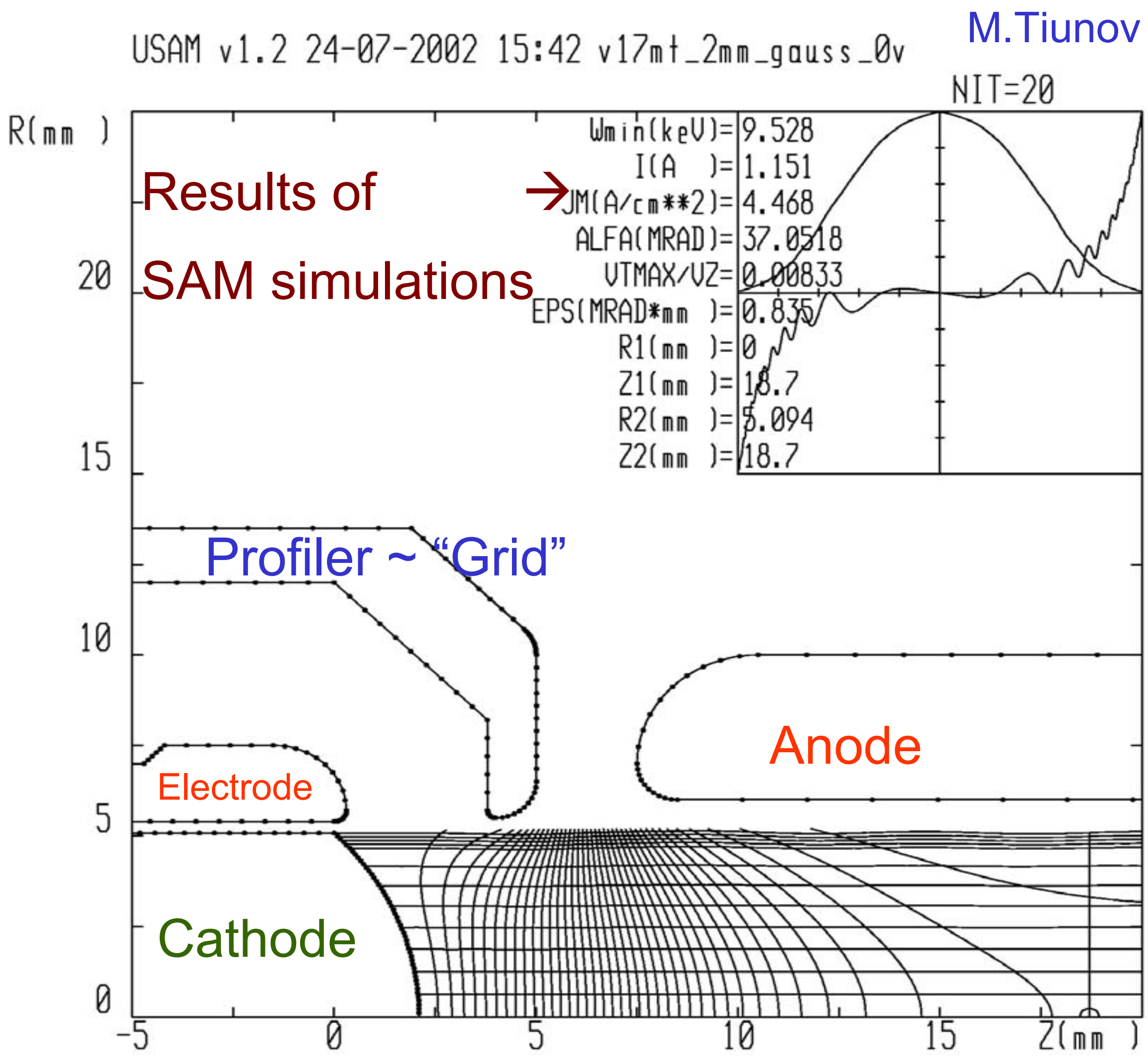
Outstanding Issue with BBC in '01-'02 – limited lifetime



e-beam edge = “donut collimator” A~20p mmrad



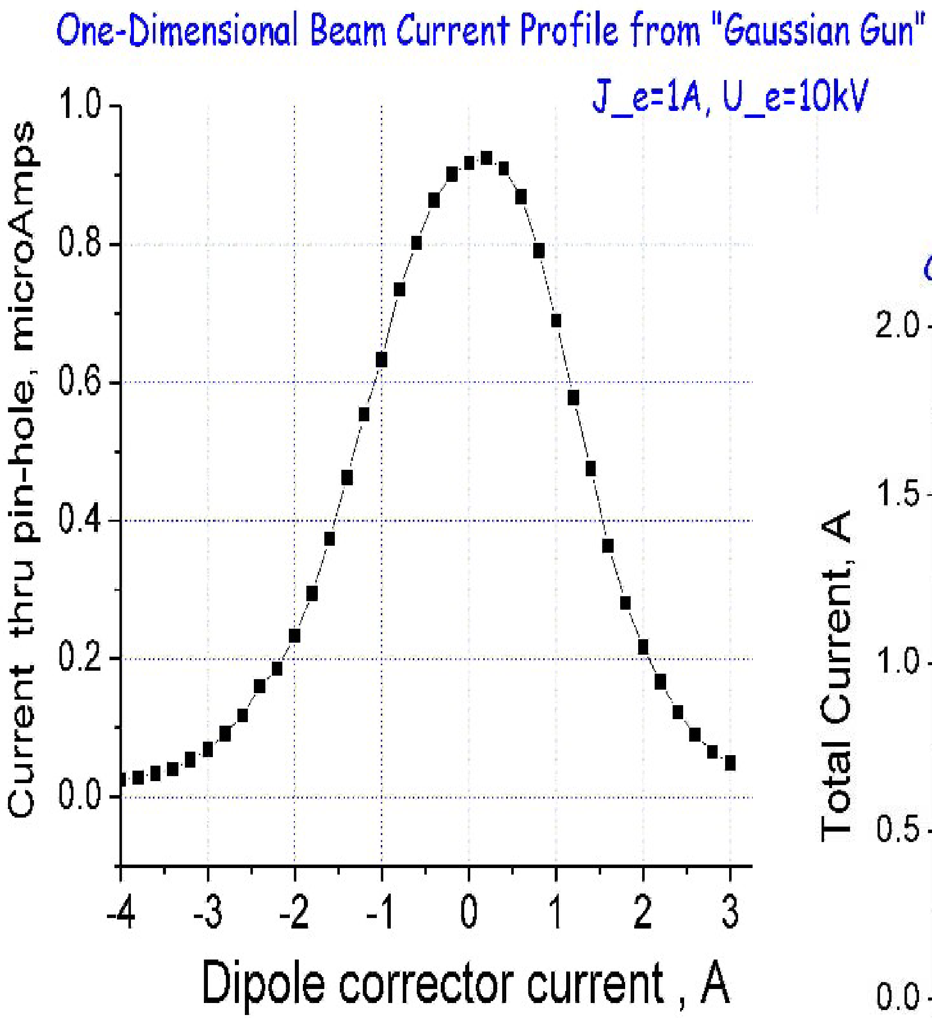
Need of Smooth Edges → Gaussian Gun

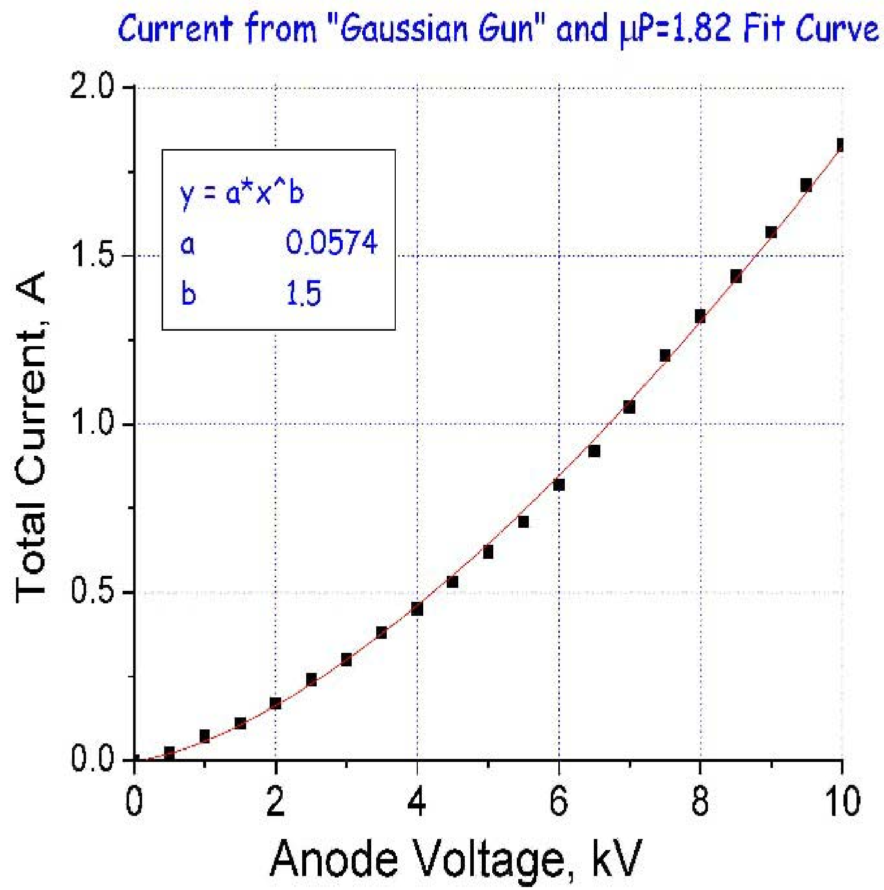


- Beam profile controlled by special electrode
- Somewhat reduced current density in the center → need of higher voltage
- Installed in Jan'2003

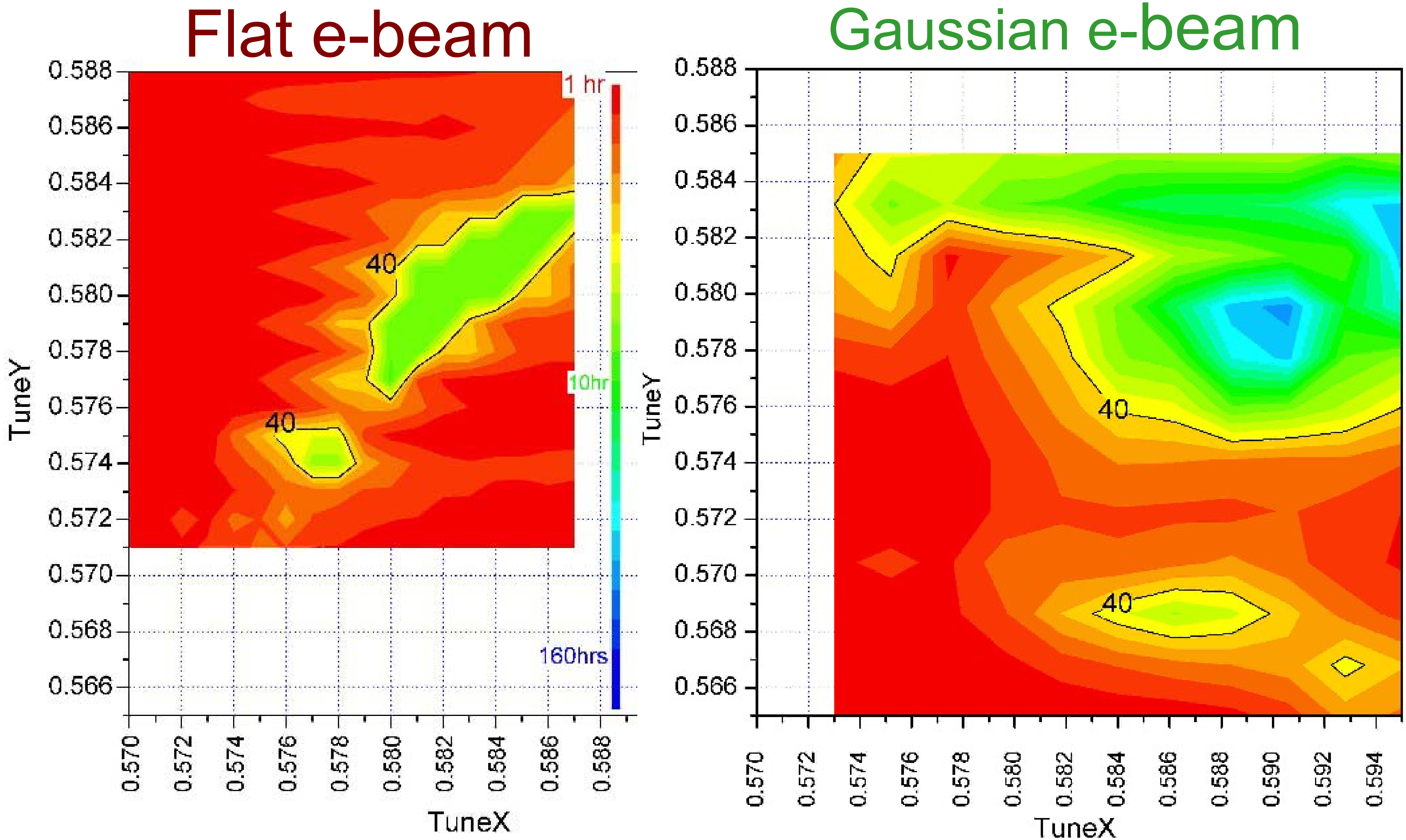
TEL Gaussian Gun – Installed Jan'03

G.Kuznetsov,
K.Bishofberger
N.Solyak





Lifetime vs WP with dQ_{TEL}~0.004



Successful Attempt of BBC with TEL

- first, the lifetime improvements with Gaussian gun made sense of the use of the TEL in HEP stores:

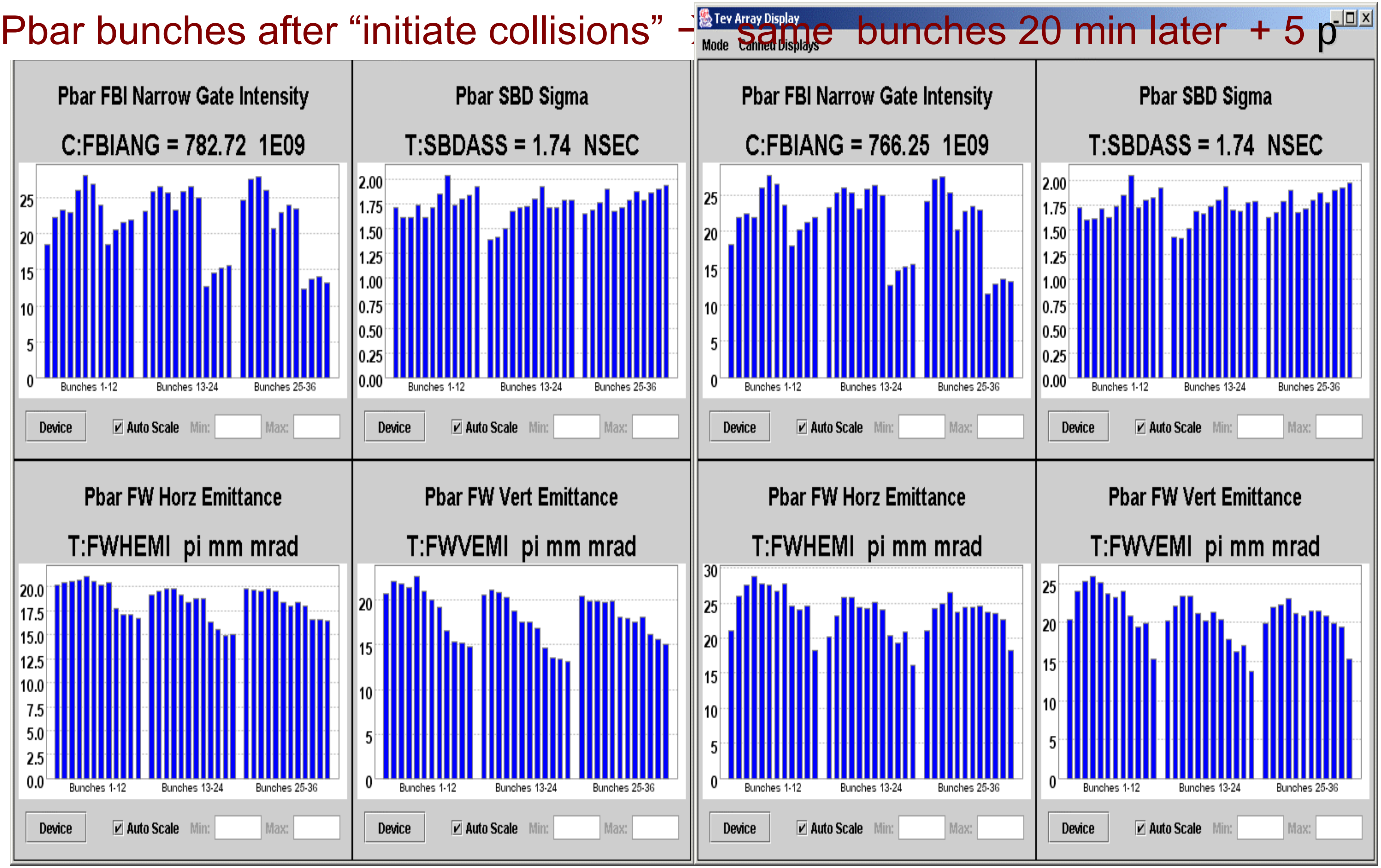
  $t_{TEL} \sim$ 100-160 hrs $>$ $t_{pbar} \sim$ 30-50 hrs

- second, it was demonstrated that the TEL can be transferred from DC beam removal regime to BBC regime (includes still manual changes of U_cath, P_fil, triggering from 3/7 to 1/1, timing and pulse width, and use of strong dipole correctors to move e-beam on pbars) and back – <u>with no significant effect on colliding beams or detector backgrounds</u>

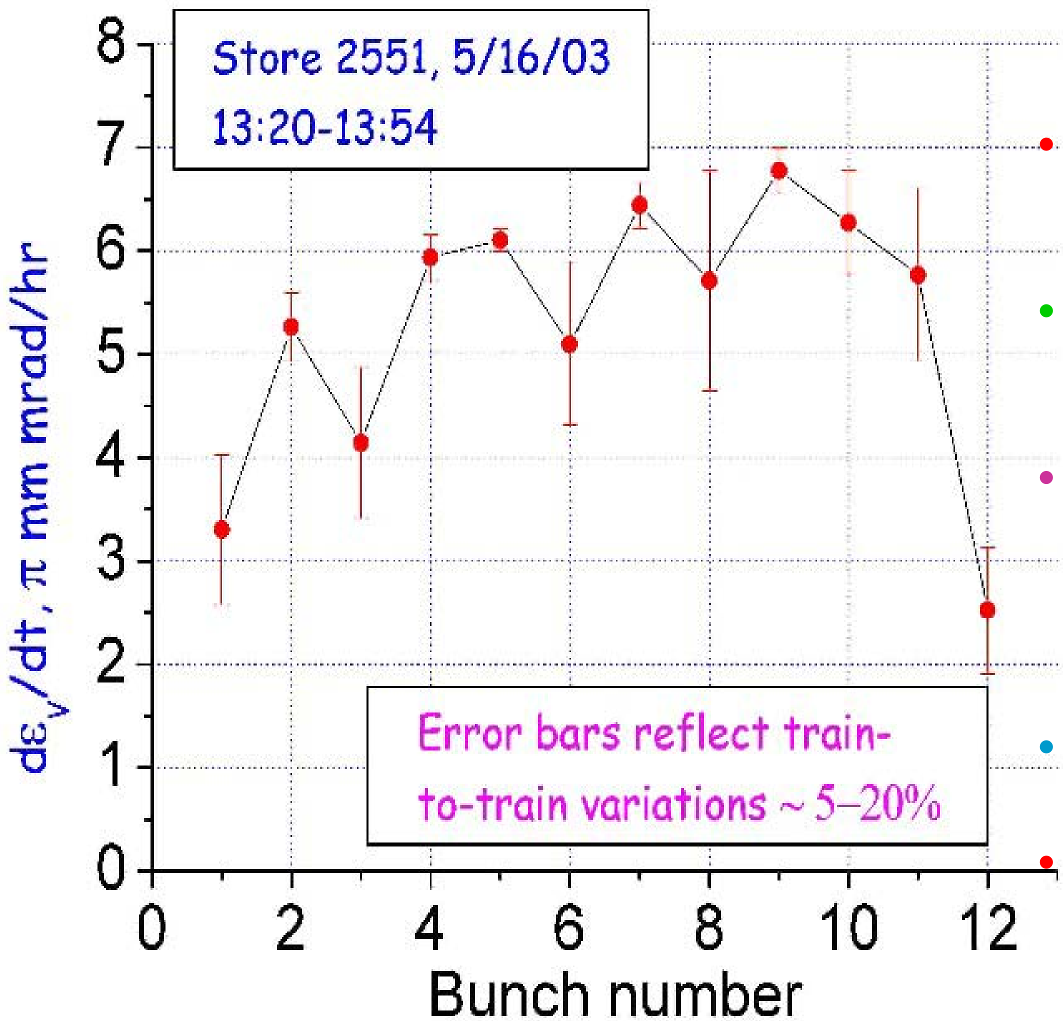
- after that the TEL with some 0.6A of current was timed on single pbar bunch at the beginning of the Tevatron stores and **<u>it was observed that the TEL can slower vertical emittance growth of antiprotons ("reduce scallops")</u>**

“Scallops” : Specific Emittance Blowup

Pbar bunches after “initiate collisions” → same bunches 20 min later + 5 p



Pbar Vert Emittance Growth Rate

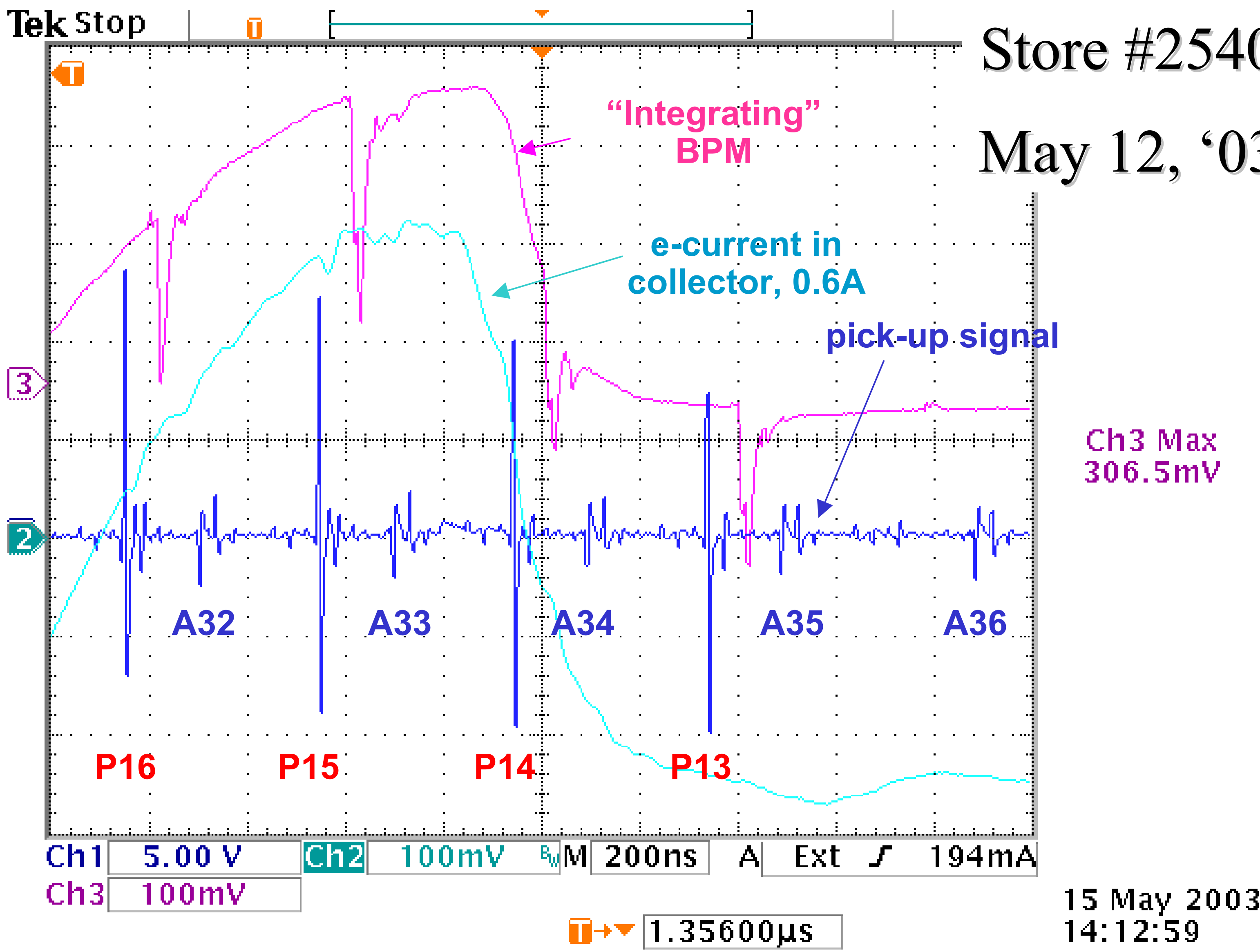


- "Scallops" is beam-beam phenomena, they started to occur after Nprotons exceeded 180e9/bunch
- "Scallops" do not take place in every store even with N_p >180e9/bunch
- "Scallops" occur in both planes, but often more prominent in vertical
- "Scallops" seem to be dependent on tunes , e.g. vertical tune change –0.002 can significantly reduce scallops
- Small "scallops" are seen in protons
- Scallops are the same in all three trains of bunches (variations <20%)

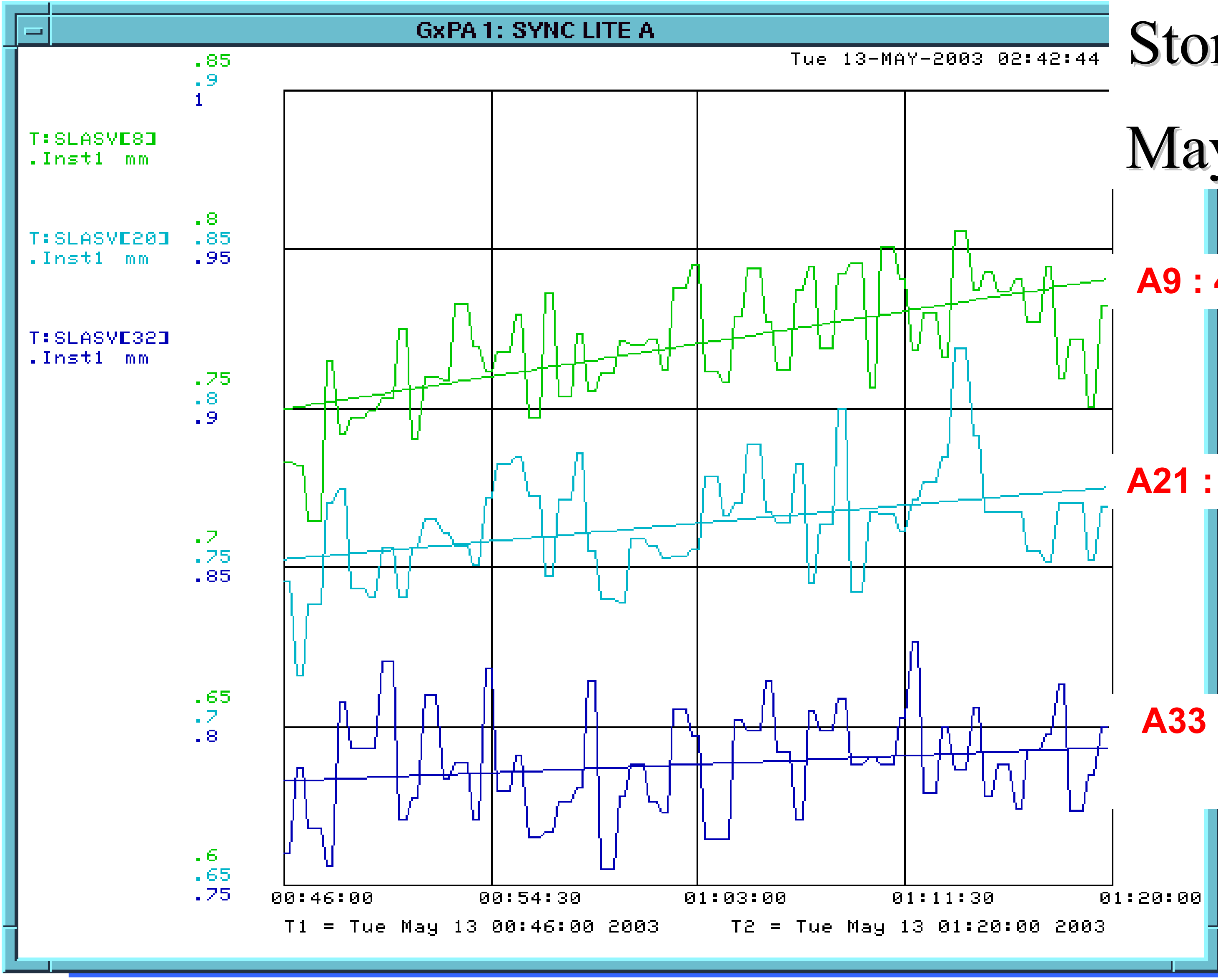
BBC with TEL: e-Pulse on A33

Store #2540

May 12, '03



Pbar V-Sizes 34 min after p-pbar collisions initiated



Store #2540

May 12, '03

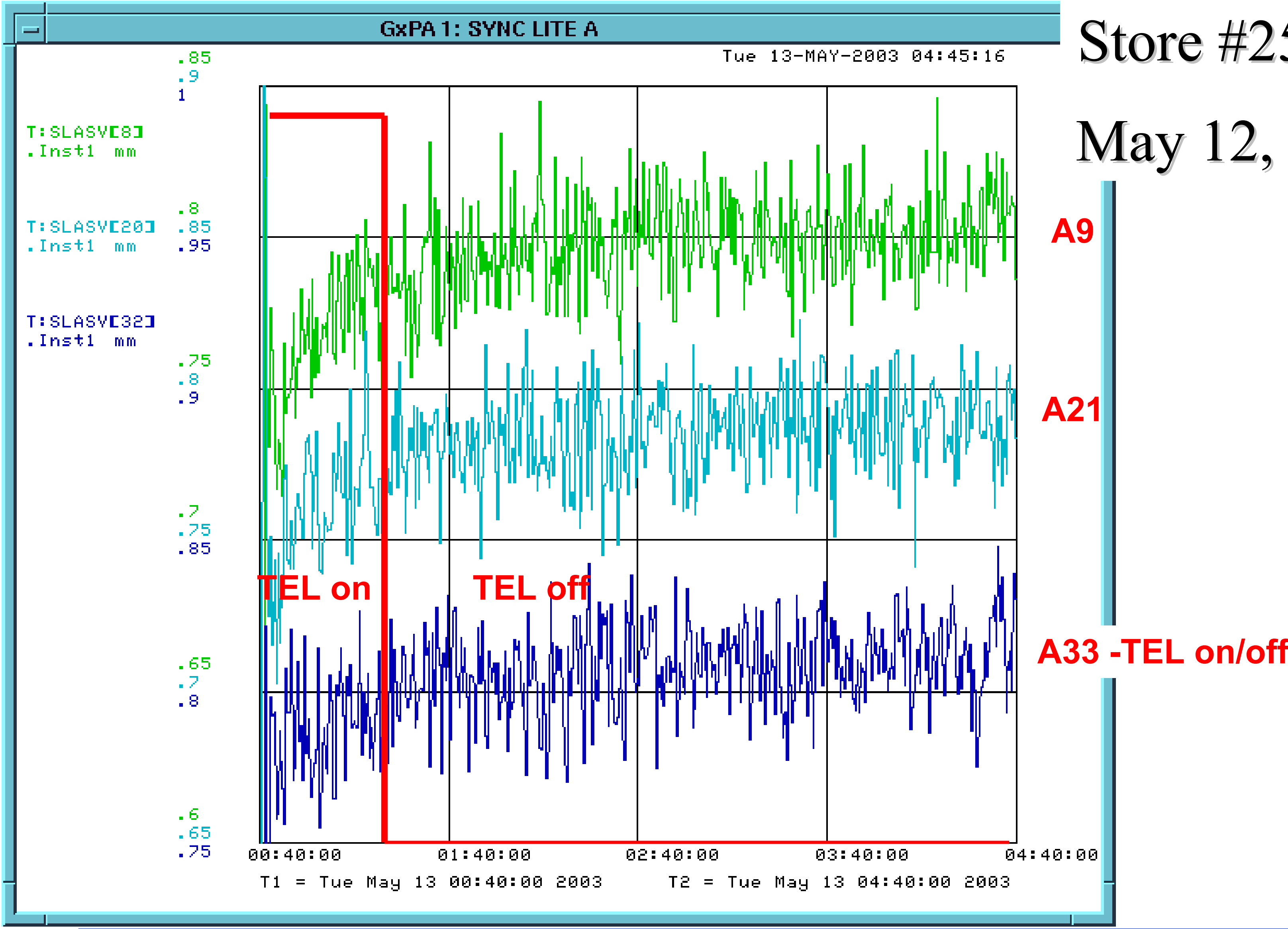
A9 : 4.1 p mm mrad/hr

A21 : 2.2 p mm mrad/hr

A33 : 1 p mm mrad/hr

-TEL on it

Pbar V-Sizes 4 hours after p-pbar collisions initiated



Store #2540

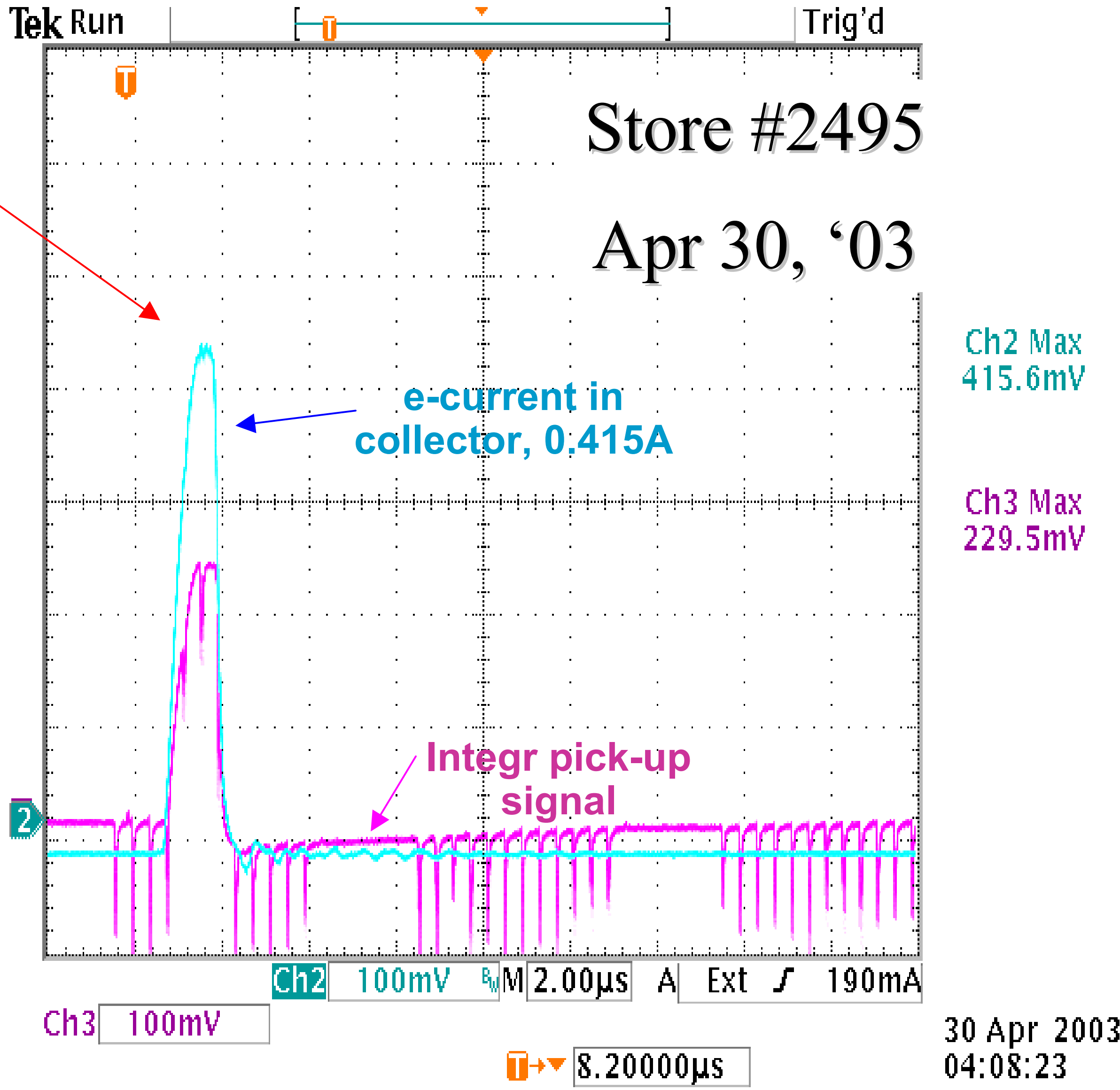
May 12, '03

Pbar V-emittance growth rates (p mm mrad/hr)

store	#A9	#A21	#A33
# 2536 (40 min)	9.9	9.2	9.3
#2538 (35 min)	1.9	1.7	2.8
#2540 (34 min)	4.1	2.2	1.0
#2546 (30 min)	3.9	1.9	4.0
#2549 (26 min)	4.5	3.6	7.1
#2541 (34 min)	6.7	6.6	7.0

Statistics of TEL used for BBC

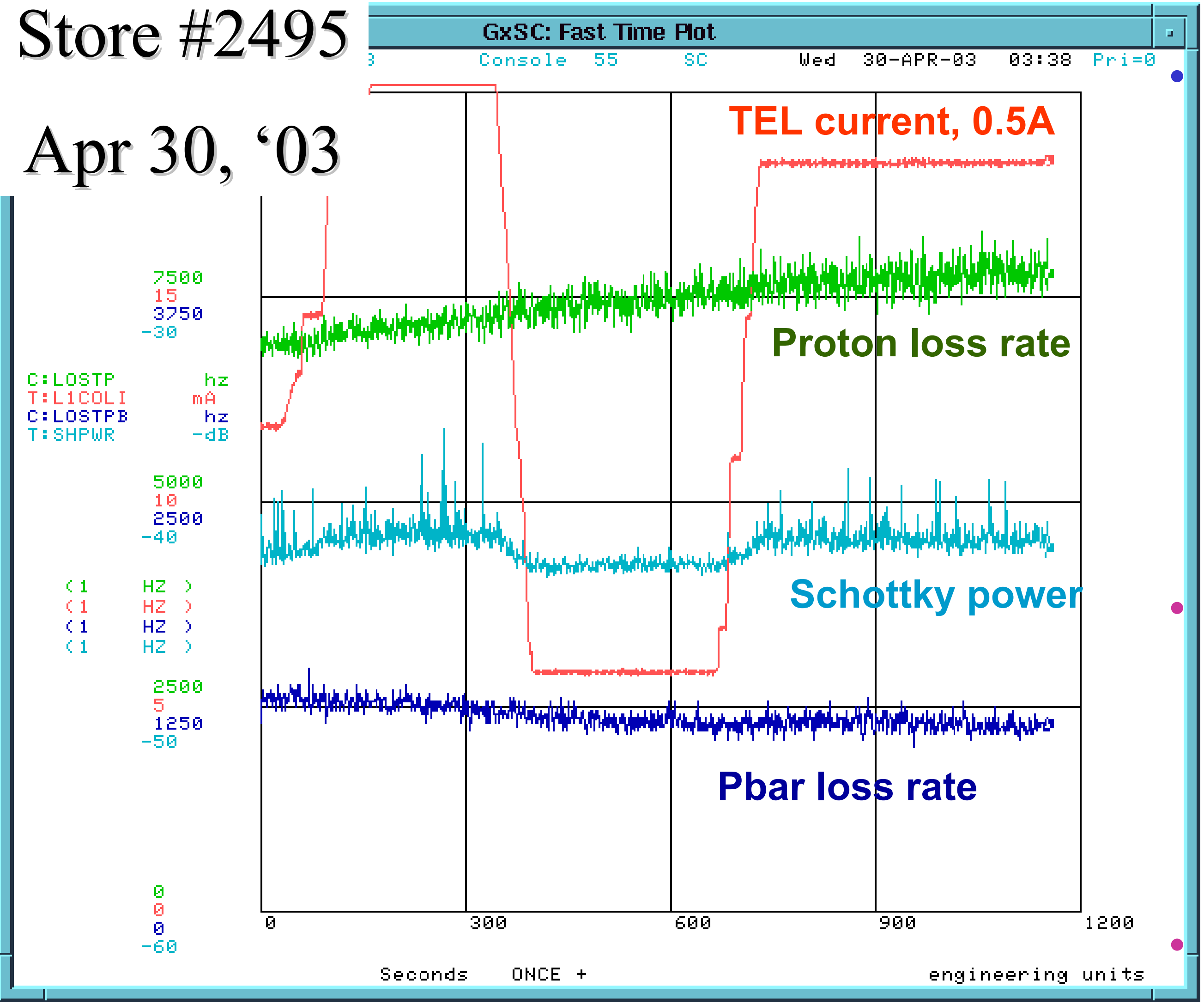
- 8 attempts since 5/20/03
- Neutral or slightly negative effect in two stores #2546, #2549 – but "scallops" occur
- No effect in three earlier stores #2445, #2490, #2495 – no "scallops"
- Positive effect in one store #2540 – "scallops" suppressed
- Faulty pulse generator led to loss of 2 pbar bunches in two stores #2487, #2502



An Example of "No Effect" Store

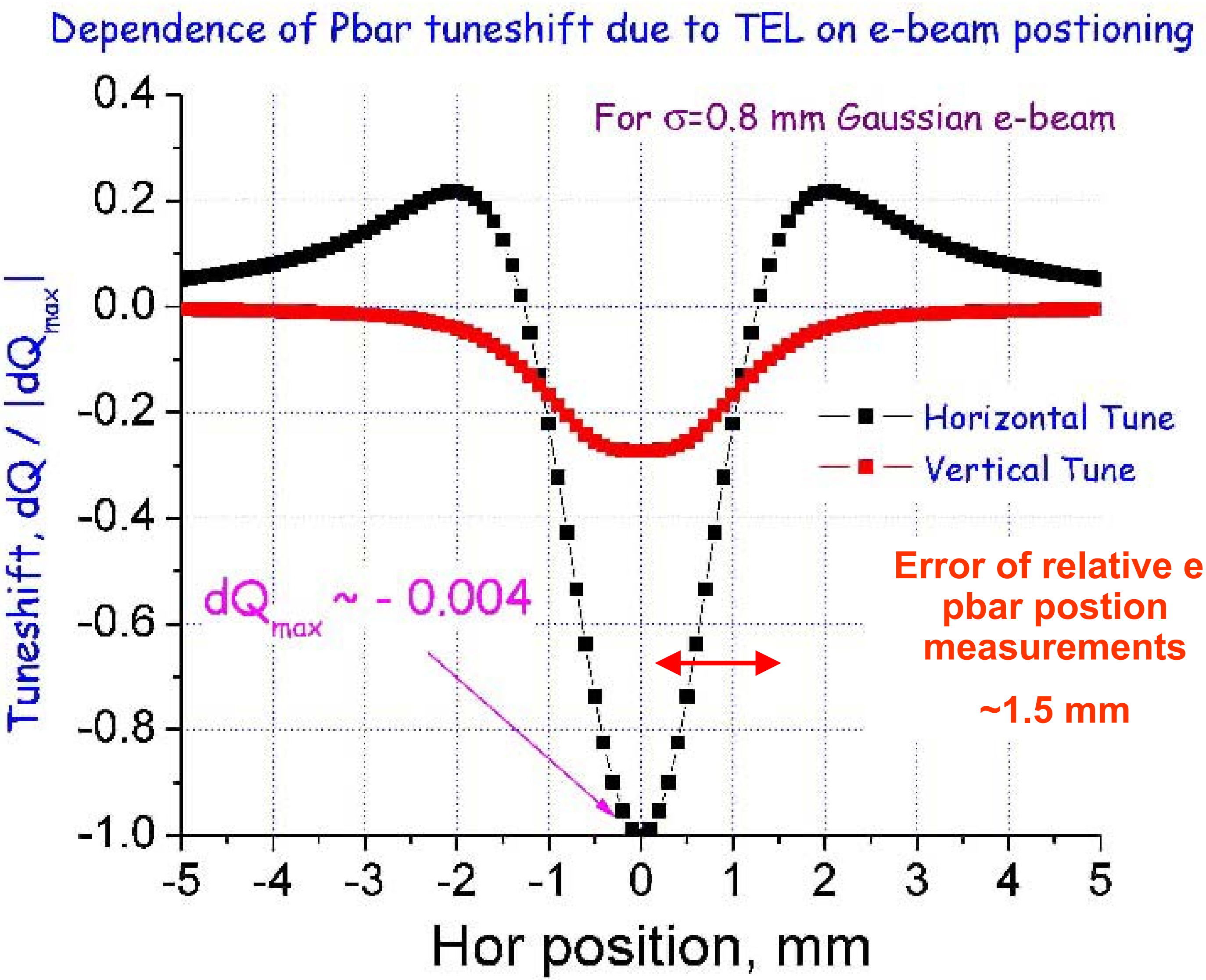
Store #2495

Apr 30, '03



- The intention was to use the TEL on few pbar bunches and shift their vert tune by – (0.001-0.002) to reduce their V-emittance blowup in the first 20 min after "initiate collisions"
- Unfortunately (for us) operators shifted the tune by -.001 for all pbar bunches and scallops gone
- TEL was ON A28-29 in 4 stores – no damage →

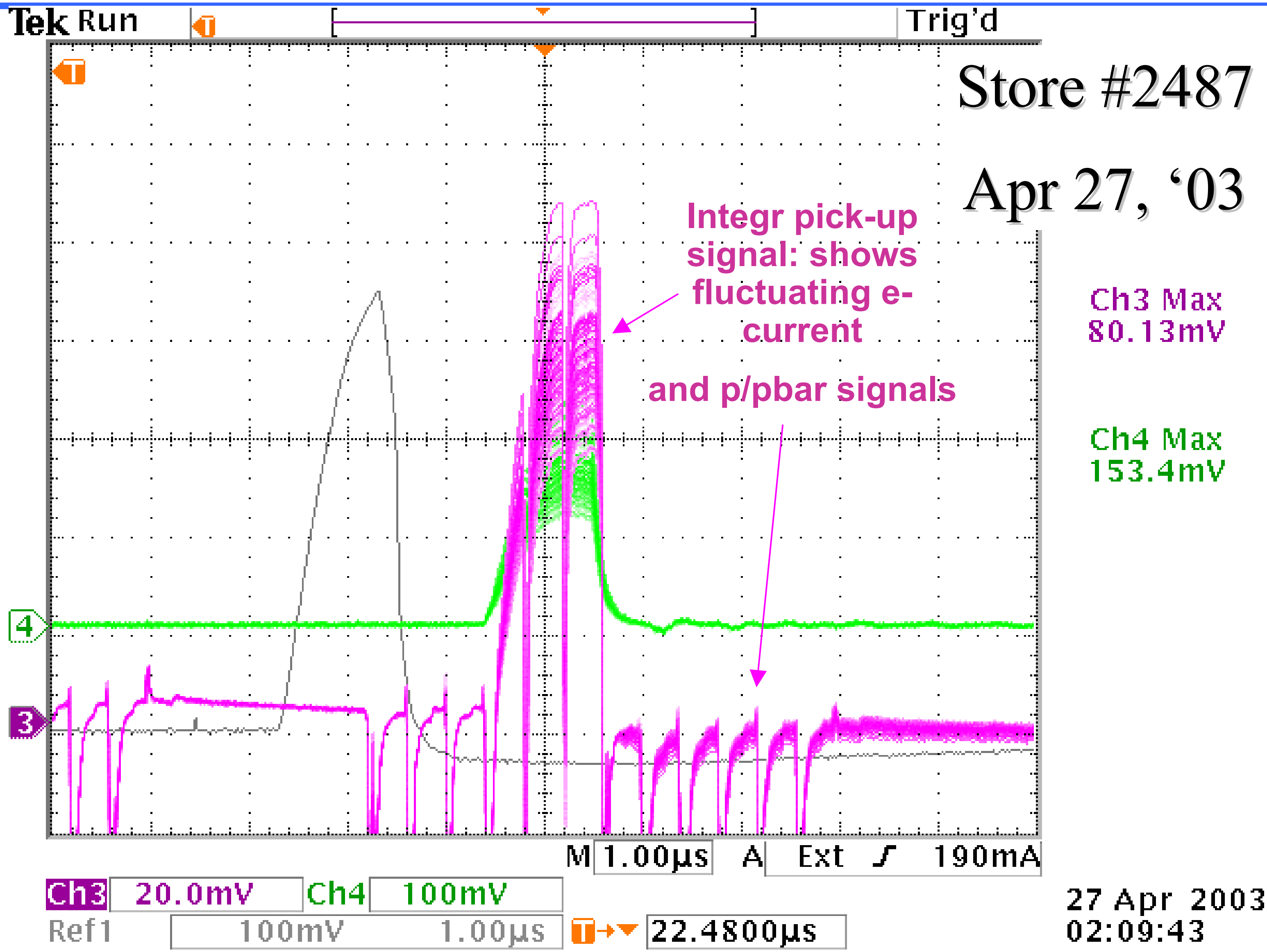
e-Pbar Alignment Seems to be Crucial



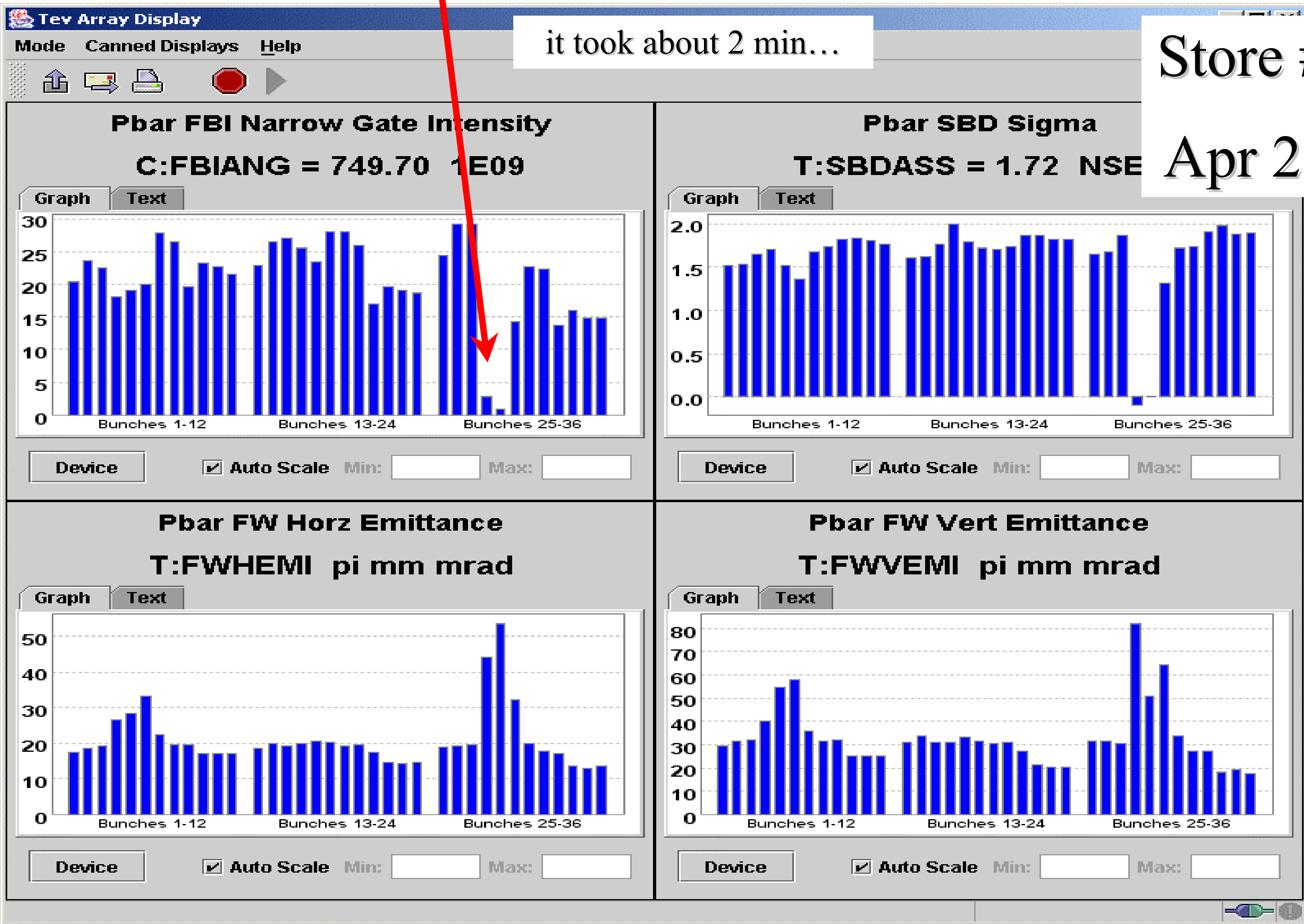
Error of relative e-pbar postion measurements

~1.5 mm

“Does it do anything at all?” – Oh, yeah!



A28-29 killed by faulty TEL triggering



Store #2487

Apr 27, ‘03

Beam-Beam Compensation:

- the first *indication* of the BBC in store #2540
- later attempts in #2546 and #2549 show that the TEL effect can be neutral or even slightly negative
- the attempts will continue
- conditions to claim *demonstration* of the BBComp:
  - scallops or other "bad" effects without BBComp
  - the "bad" effects suppressed by TEL
  - on systematic basis

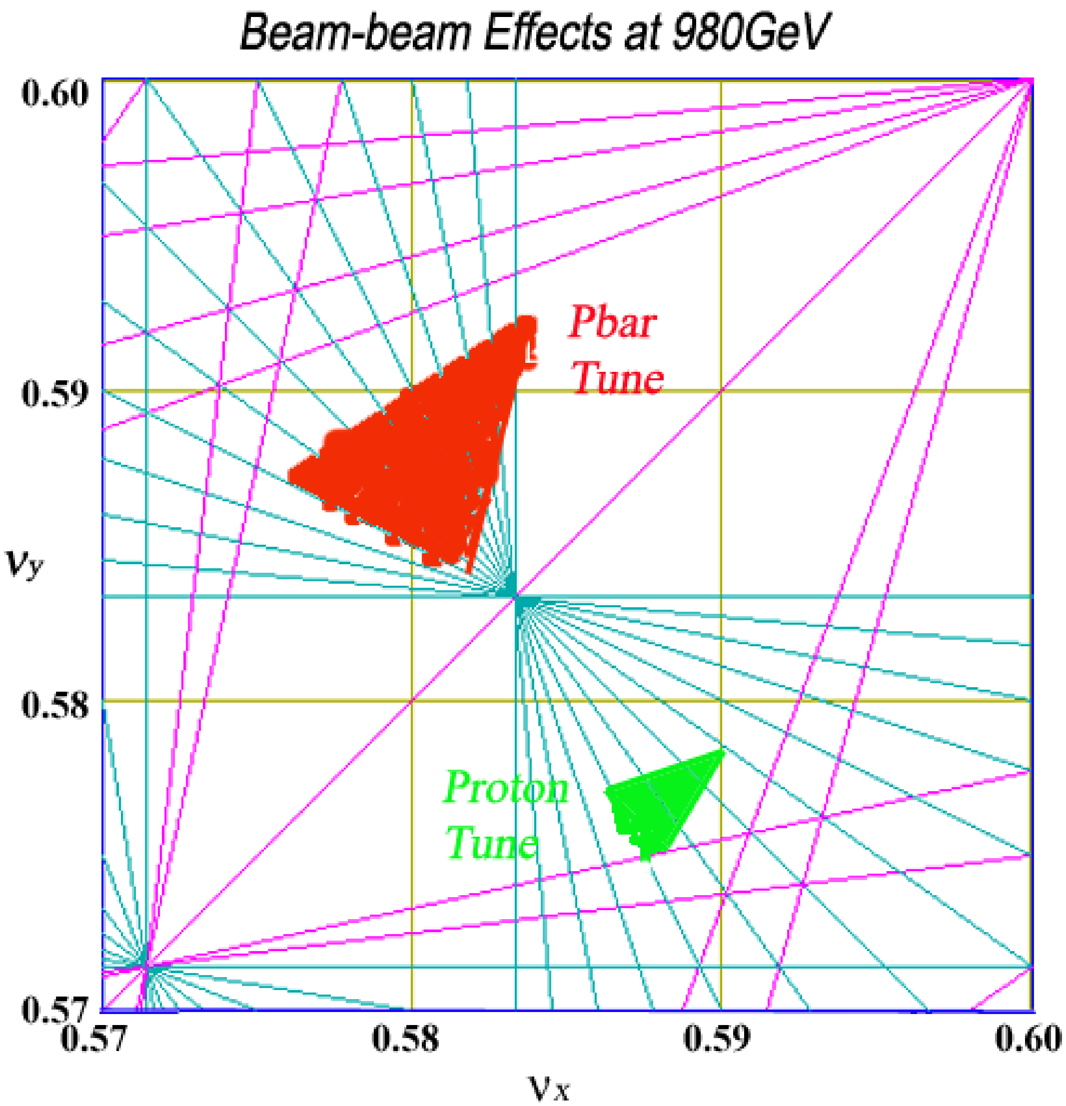
What is important for the BBComp?:

- following issues need to be resolved before the Beam-Beam Compensation will be used operationally :
  - better understand beam-beam effects in the Tevatron and parametrize them (see talks of T.Sen and Y.Alexahin)
  - improve e-pbar-p position measurements < 0.1 mm
  - single pbar bunch tune diagnostics (1.7GHz Schottky)
  - do we need wider e-beam or different shape?

What to compensate?

- Beam-beam interaction in the Tev leads to
  - Pbar losses at injection energy 150 GeV
    - 15% → 3%
    - Long-range BB
  - Pbar losses on ramp
    - 5-15%
    - Long-range BB
  - Pbar and proton losses during LB squeeze
    - 1-3% for pbars , of the order of 1% for protons
    - Long-range BB
  - Pbar and proton emittance growth in collisions
    - Vary from 1 to 20 pi mm mrad/hr for pbars (1/10th for p's)
    - Head-on and Long-range
  - High proton and pbar losses (poor lifetime) in stores
    - Can be as small as 20 hrs for both beams → detector bckgrnd
    - Head-on and Long-range

Tevatron Working Points



• with current parameters

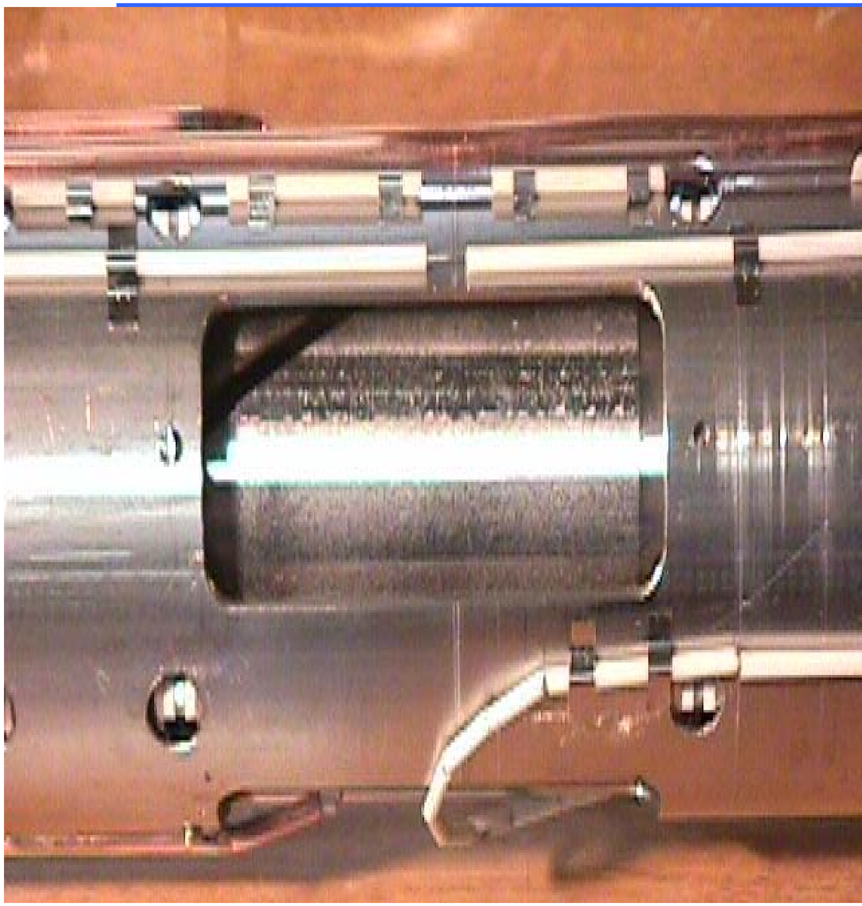
N_p ~ 250e9/bunch , emittance ~ 20 pmmmrad

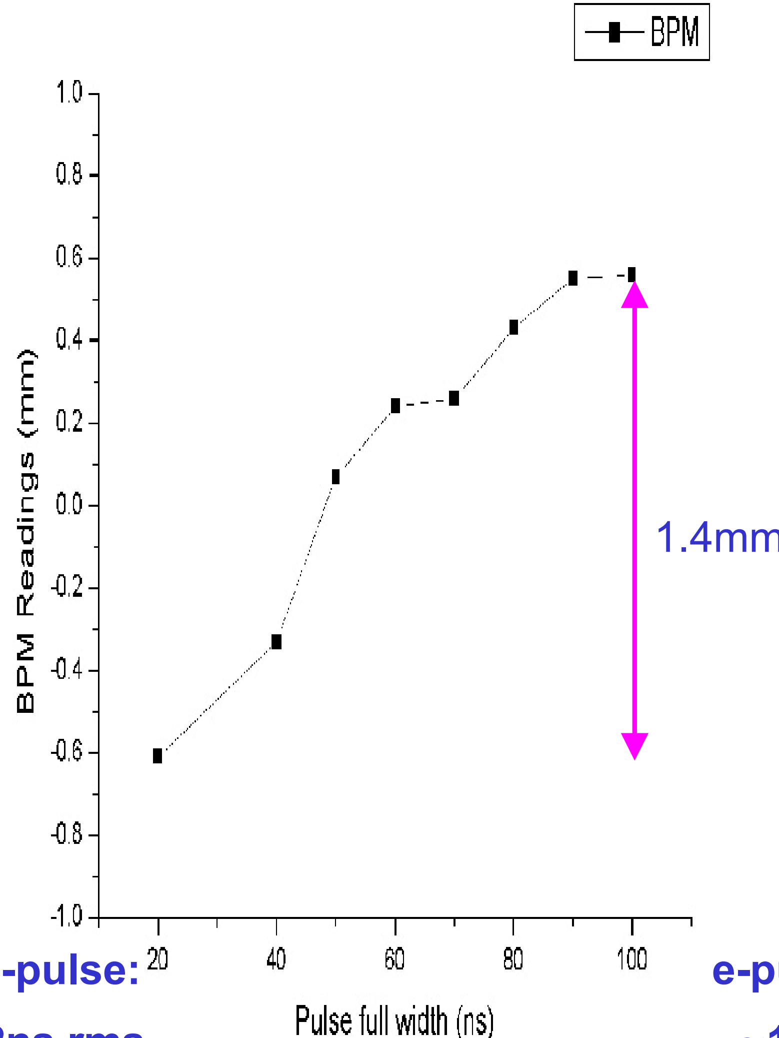
Head-on tuneshift is x~ 0.015

Bunch-by-bunch tune spread
dQ ~ 0.003-0.005

B-B dynamics dominated by 5th, 7th, and 12th order resonances

TEL BPMs – Need to Be Improved



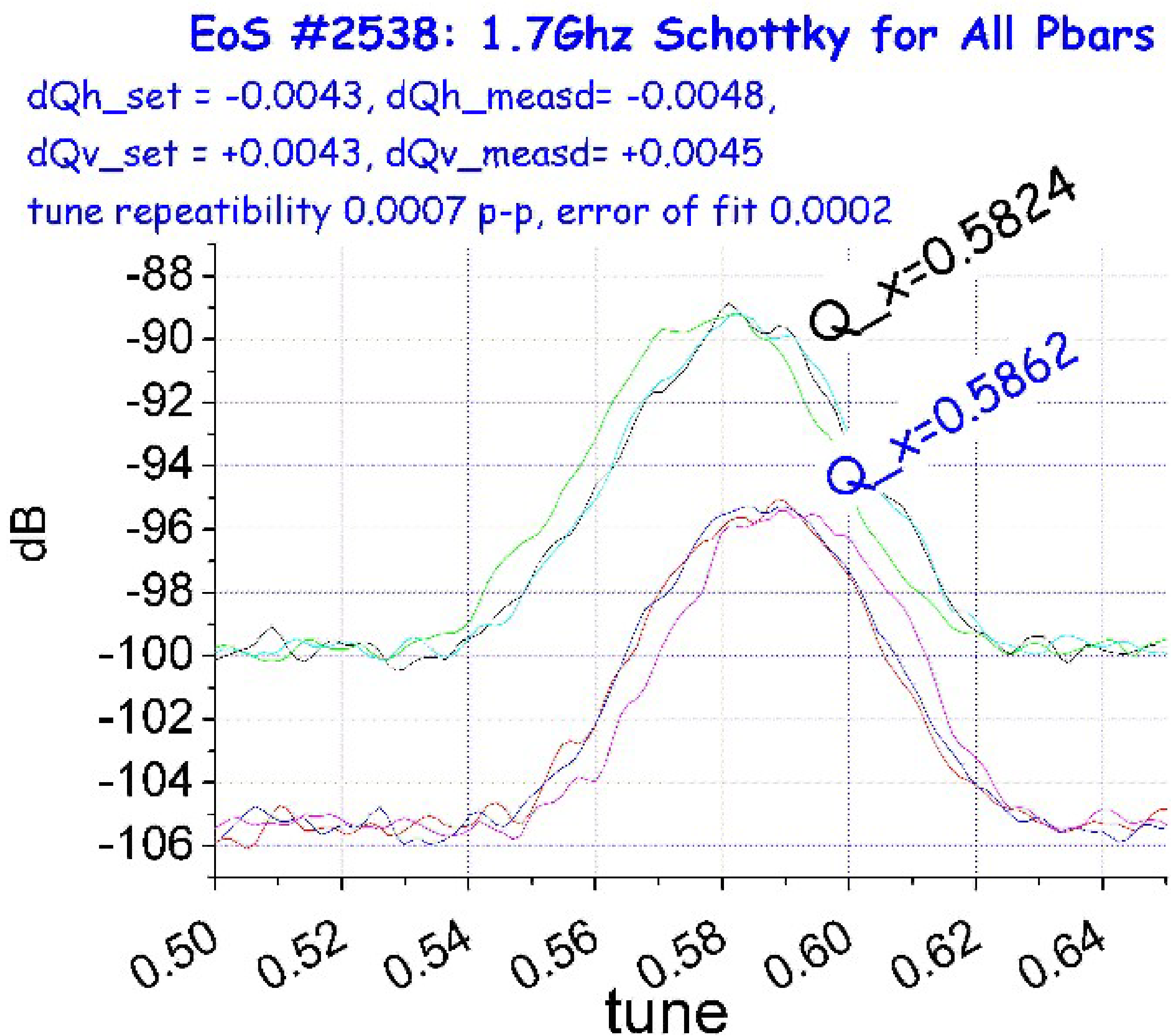


p-pulse: 2ns rms

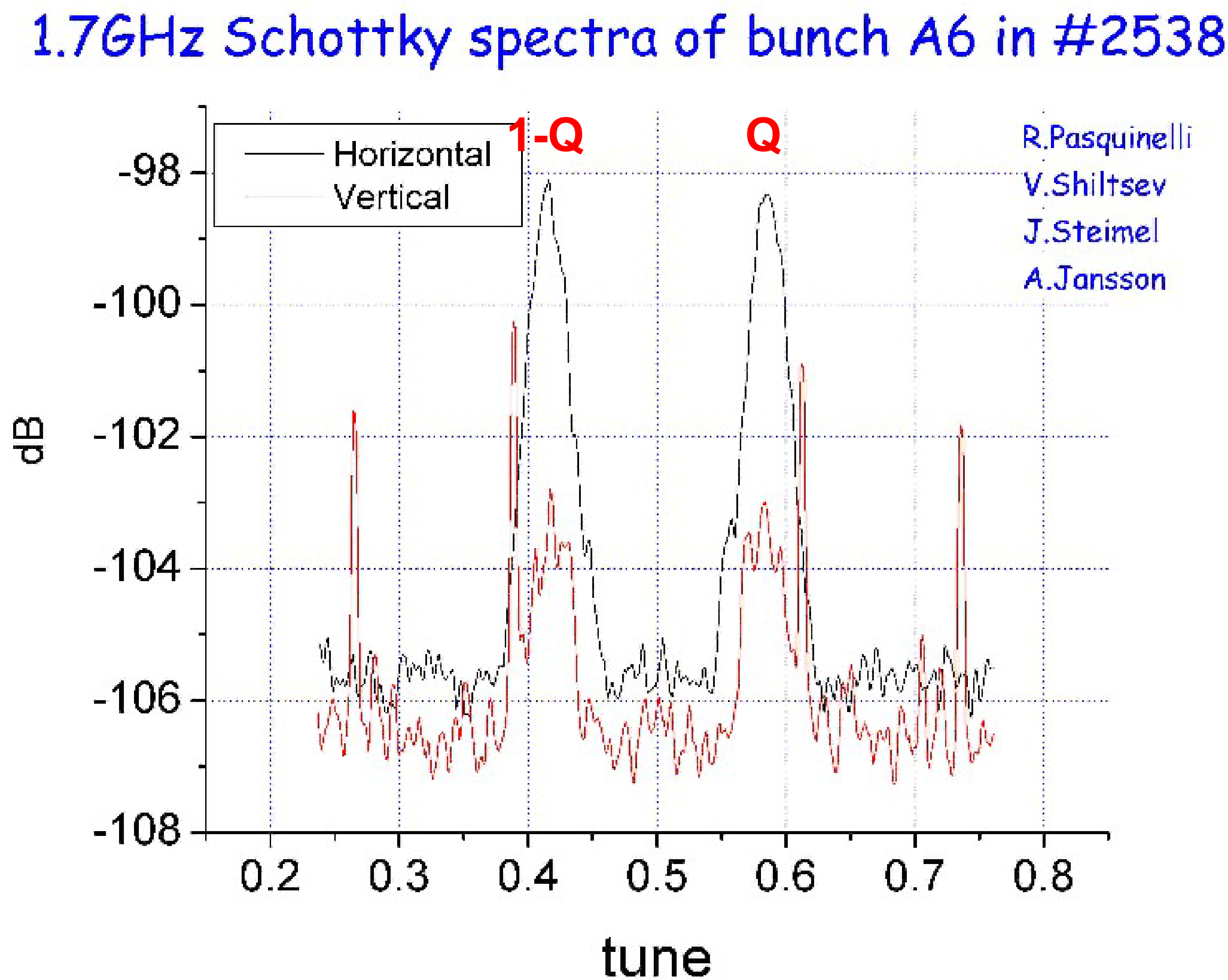
e-pulse: ~1 ms

- *Calibrate BPMs X(f) in the tunnel with variable pulse generator - need access*
- *Calibrate BPMs using longitudinal waves in e-beam excited by protons - need study time*
- *Install new BPMs – already designed, tested – need shutdown*

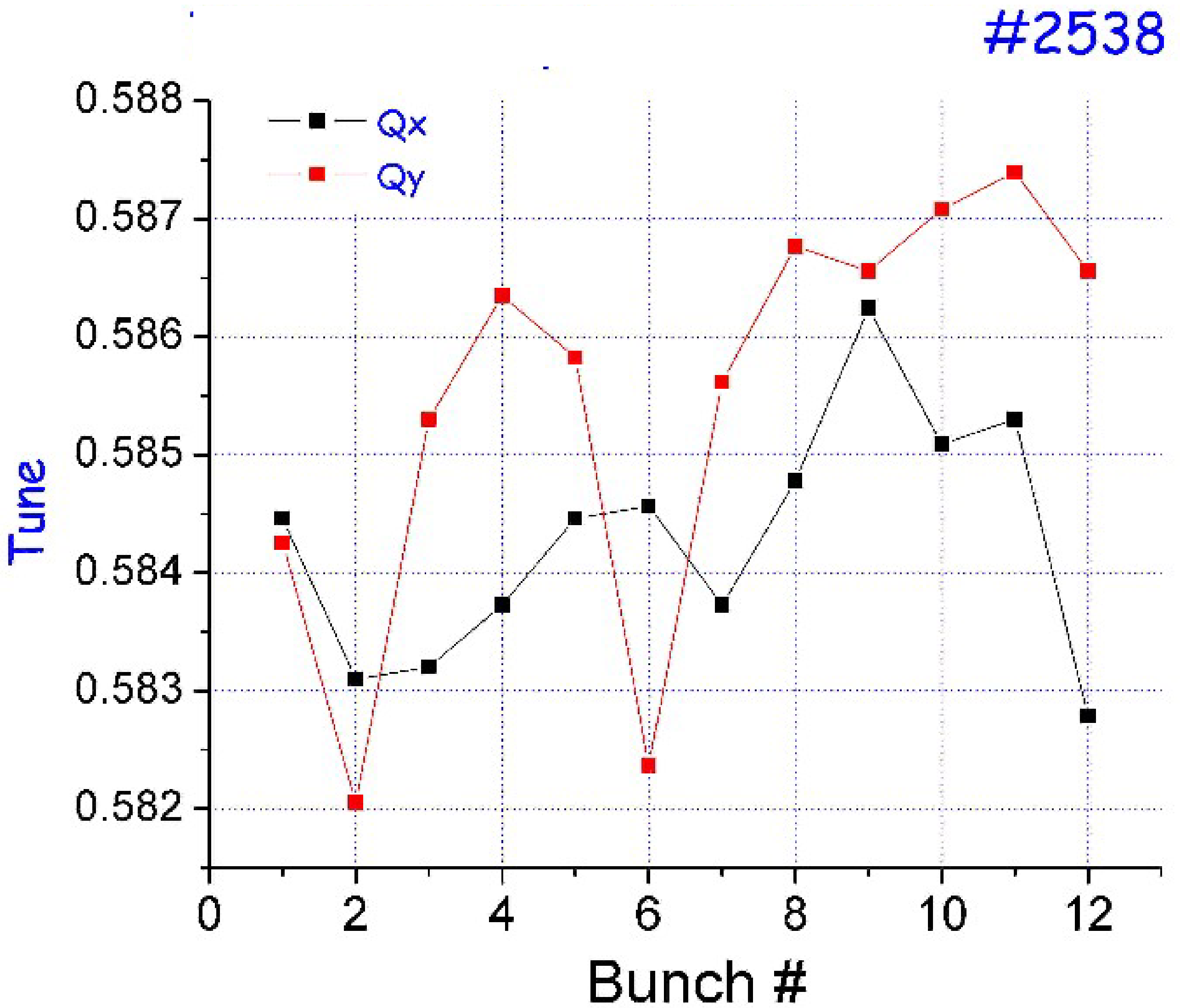
1.7GHz Schottky Spectra



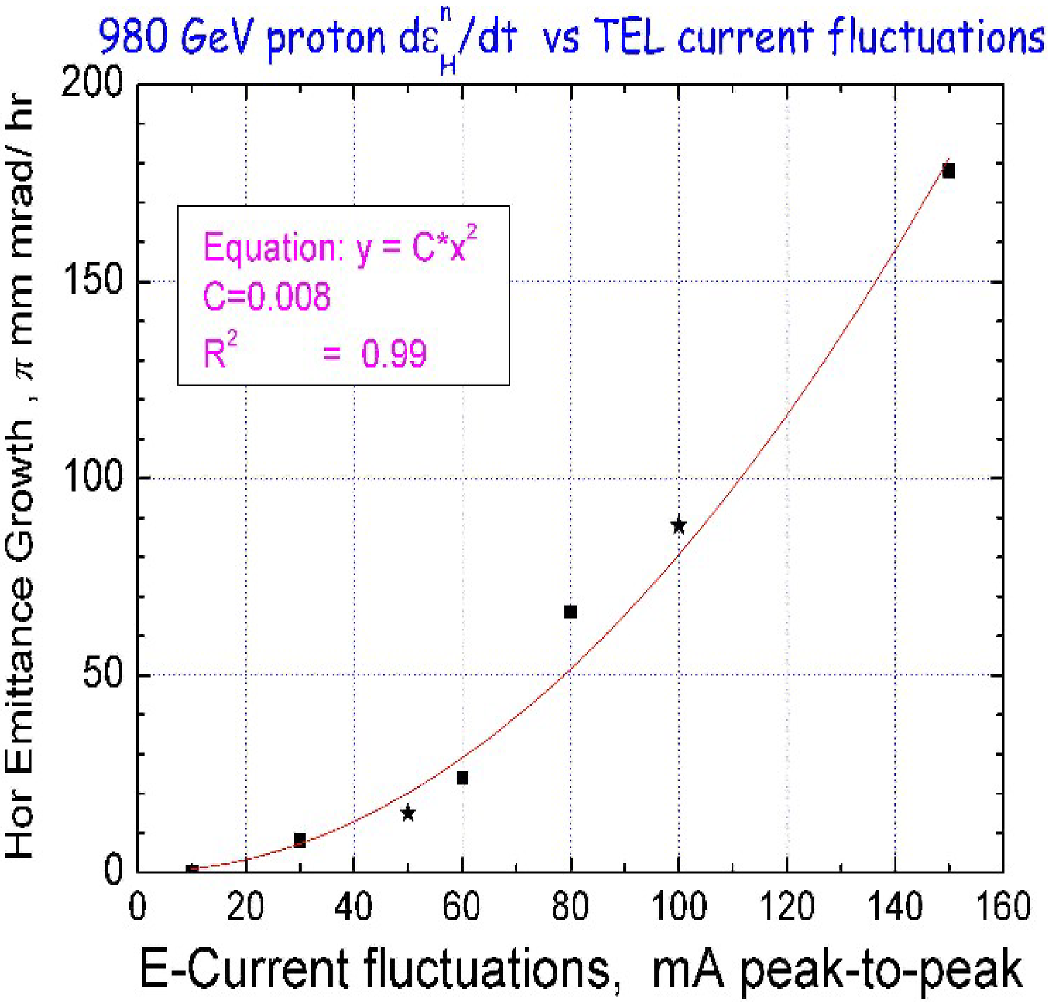
Tevatron 1.7GHz Schottky Spectra



Pbar Bunch Tunes Measured by 1.7GHz Schottky detector



Other Issues: e-Stabilization (needed?)

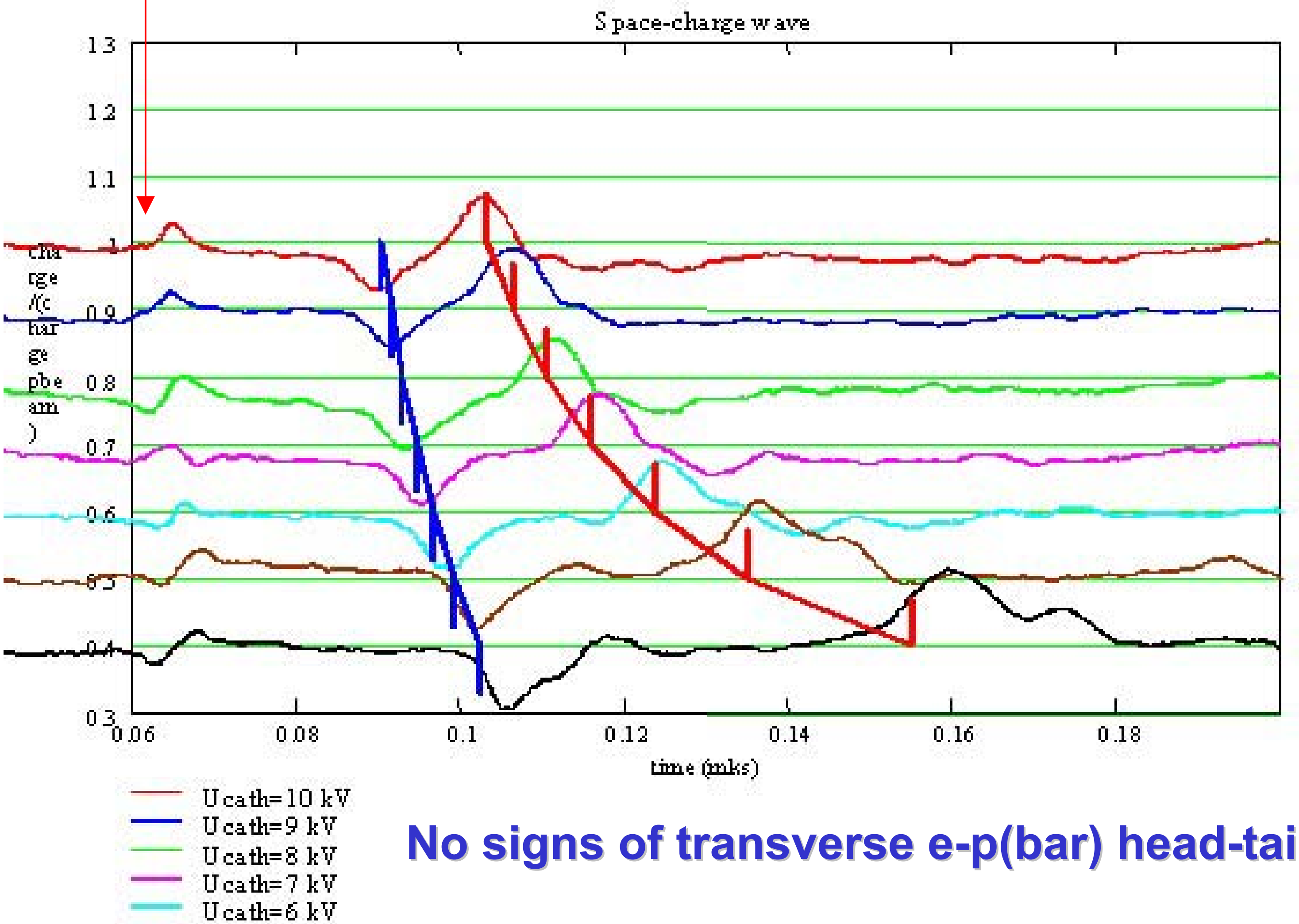


- TEL e-current turn-by-turn noise amplitude dJ_e ~3-5mA p-p
  while operating for BBC
  with dQ > 0.005
  → 0.1-0.2 p/hr
- That is less though comparable with "natural" emittance growth of 0.2-0.5 p/hr
- → we plan to consider possibilities for dJ_e and dX_e stabilization

Electron SC Waves Excited by Protons

Passage of protons

V.Parkhomchuk, V.Reva, V.Shiltsev



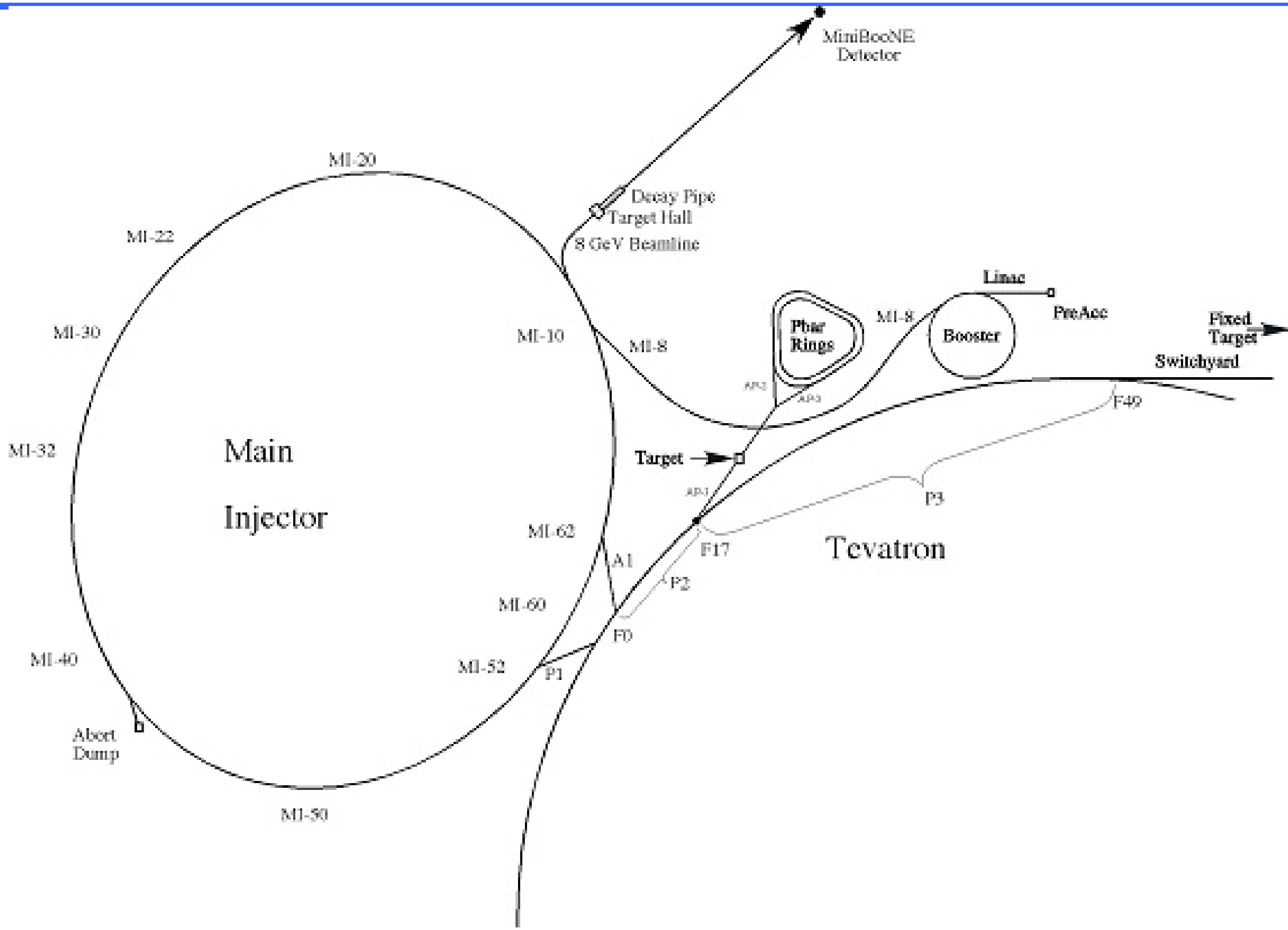
No signs of transverse e-p(bar) head-tail instability

Summary

- Status:
  - max dQ~0.009 tuneshift achieved
  - p(bar) lifetime deterioration proved to be due non-linear beam-beam force due to e-beam edges ("soft collimator")
  - after installation of Gaussian e-gun, p-beam lifetime of ~160hrs has been achieved (compare with 40 hrs in stores)
  - TEL was used in several stores recently and we've got first indications of successful beam-beam compensation : vertical emittance growth rate was reduced for pbar bunch #33 early in store #2540
- Work to do:
  - continue to explore BBC at 150, ramp, LB for both pbar and p
  - improve diagnostics (TEL BPM, Pbar Schottky tunemeter, etc)
  - wider e-beam
  - better beam current and position stabilization
  - the second TEL is under construction but the BBC is not the major motivation (← spare for the DC beam removal)
  - new HV pulser (~ 15kV instead of 7kV, shorter pulse)

Back-Up Slides

Beam-Beam Compensation with TEL



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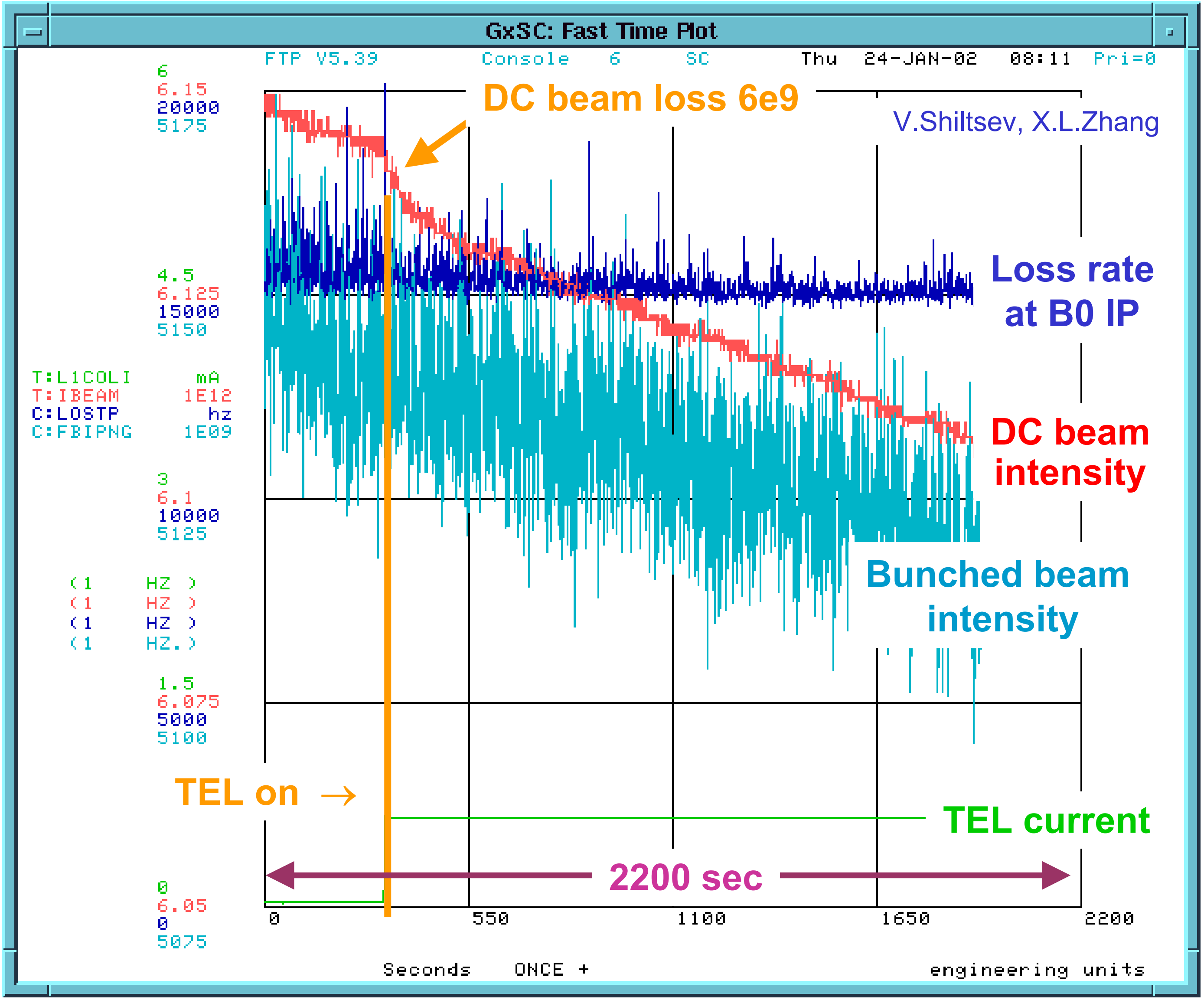
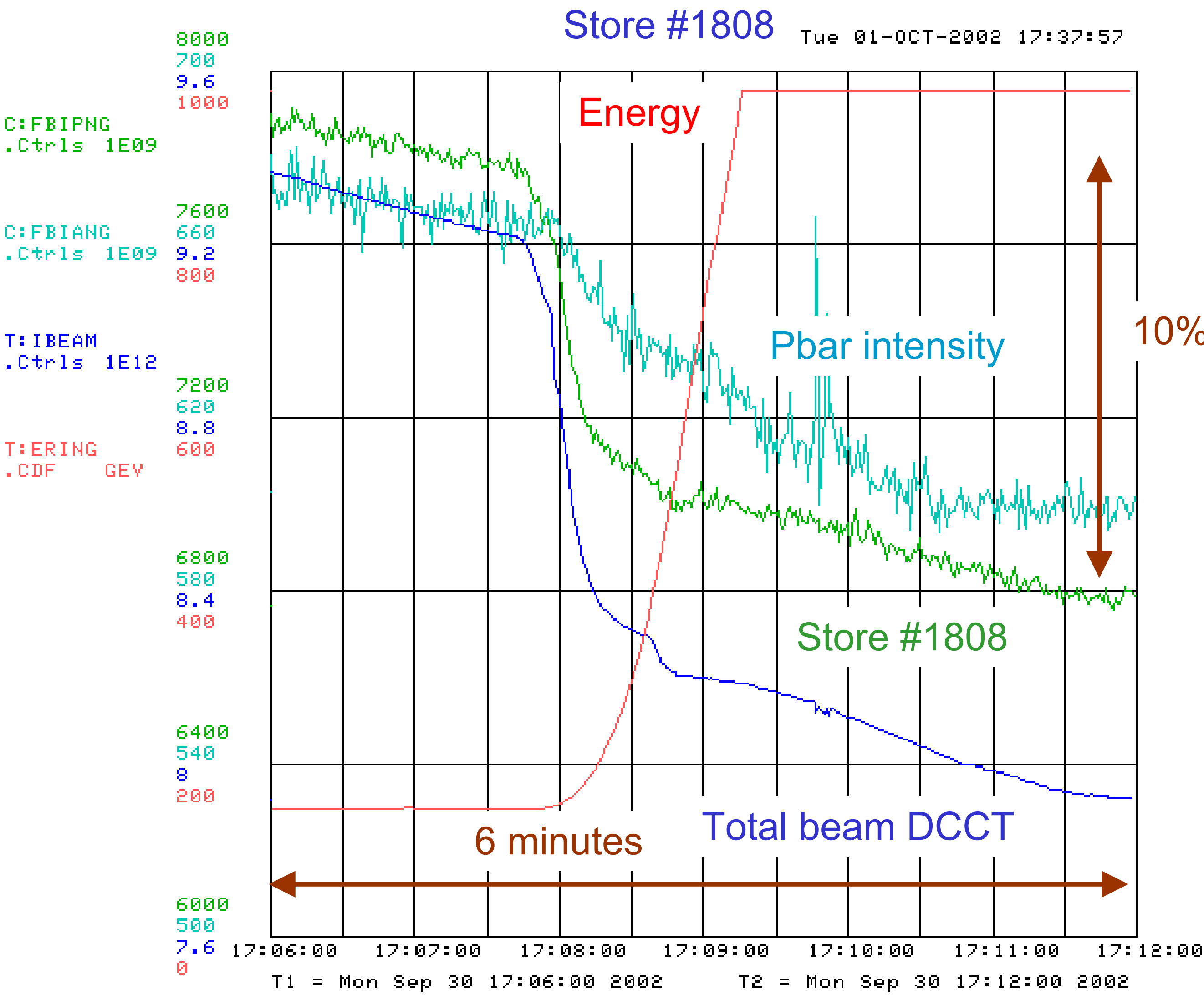
TEL as the DC Beam Cleaner

- Phenomenon not yet understood causing beam to leak out of RF buckets
- At the end of store there is anough of the DC beam in the abort gap to cause quench on abort , $>6\times10^9$ or ~0.1% of N_{total}
- e-beam placed to edge the p-orbit helix
- Fire TEL in 3 gaps every 7 turns to excite resonance
- TEL is equivalent to 100kW “tickler” (vs 50W in Q-mtr)
- TEL reduces DC beam intensity and eliminates spikes in the CDF losses
- currently TEL is operational: now it is turned ON early into each store, then OFF after store terminated (no TEL at injection as the DC beam is not a problem there)
- When needed, TEL is used for p/pbar bunch removal

Removing DC beam with TEL

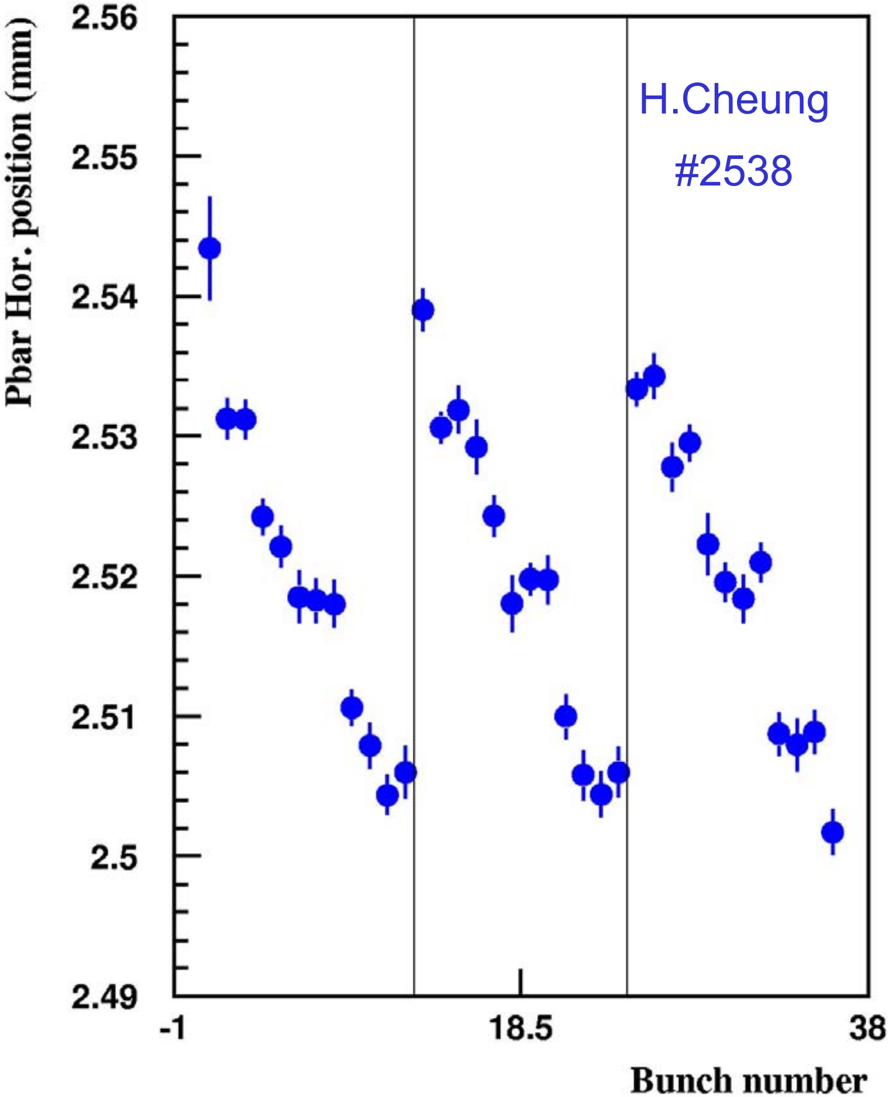


Beam Loss on Ramp



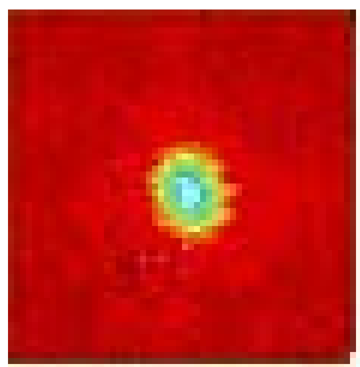
- (intensities are zero-suppressed)
- at the very beginning of the ramp DC beam is lost (some 2-3% in both p and pbars, depends on injected longitudinal emittance)
- then we have significant beam loss on ramp which – at smaller rate – continues at flat top and in squeeze
- For pbars, the reason is beam-beam interaction
- For protons - ? →

Long-range B-B Seen by SyncLite Monitor

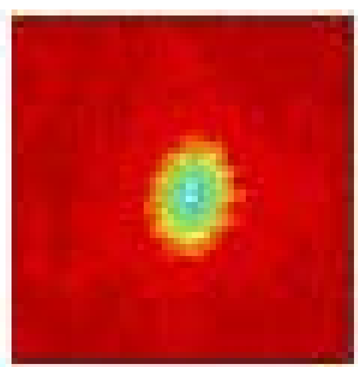


- SL reports s, mean, N, tilt bunch-by-bunch for both protons and pbars
- SL reports scallops (when they appear) in good agreement with FWs
- It also shows 40 micron b-by-bunch hor pbar orbit variation along the bunch train with 3-train symmetry (4 microns for protons)

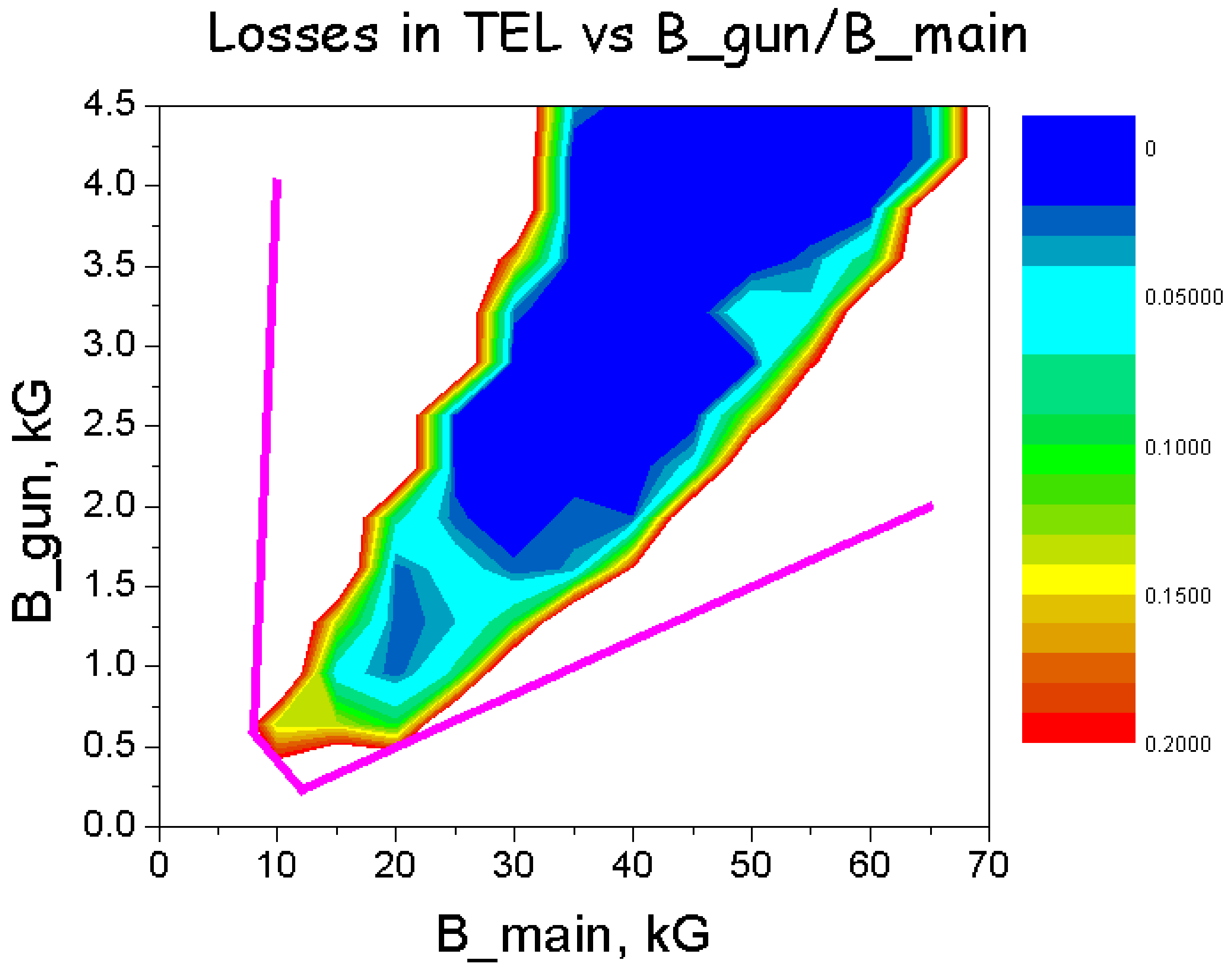
Bunch #1



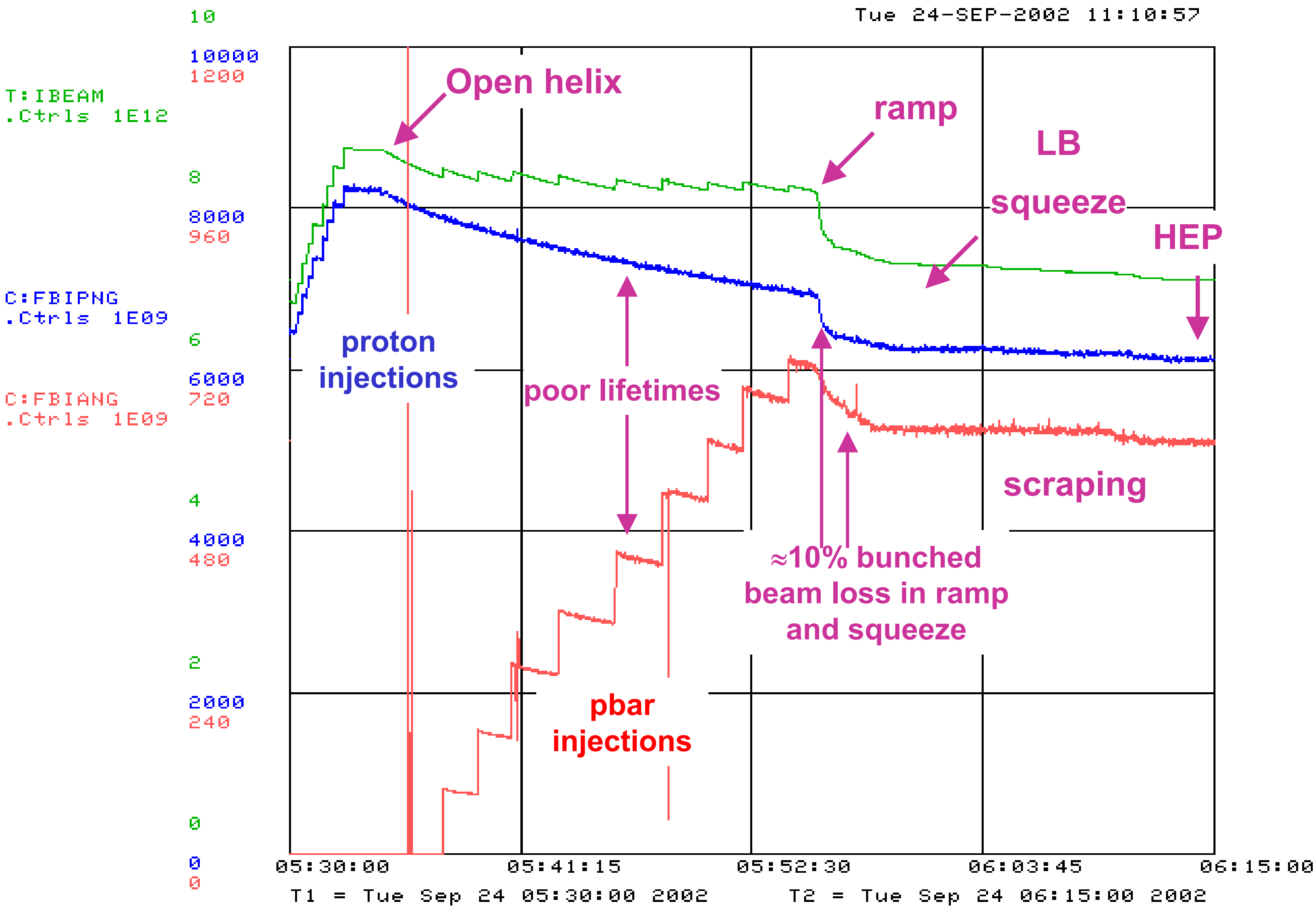
Bunch #8



Tramsmission region of the TEL



Beam-Beam in Tevatron: Overview



Beam-beam Interaction As Major Factor

- *Pbar transfer efficiency strongly depends on N_p, helix separation, orbits, tunes, coupling, chromaticity and beam emittances at injection*
- *Summary of progress with beam-beam since March 2002:*

	Mar'02 *	Oct'02 **	Jan'03#	Mar'03 ##
Protons/bunch	*140e9*	*170e9*	*180e9*	*205e9*
Pbar loss at 150 GeV	*20%*	*9%*	*4%*	*4%*
Pbar loss on ramp	*14%*	*8%*	*12%*	*11%*
Pbar loss in squeeze	*22%*	*5%*	*3%*	*2%*
Tev efficiency Inj→low beta	*54%*	*75%*	*75%*	*80%*
Efficiency AA→low beta	*32%*	*60%*	*62%*	*64%*

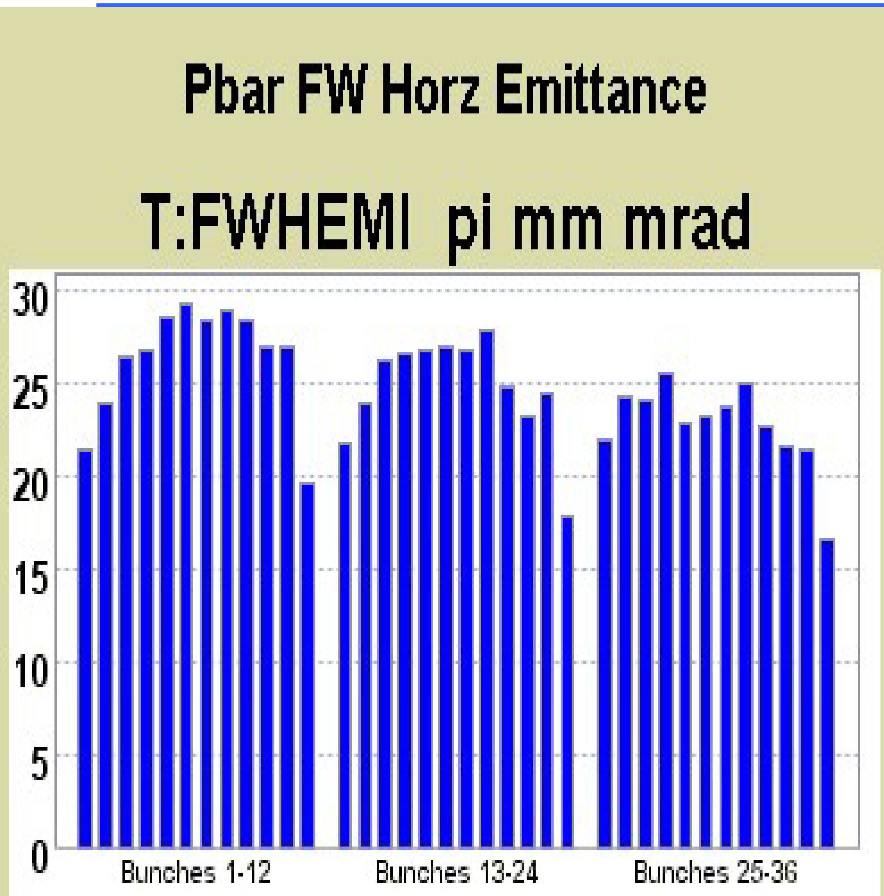
* *average in stores #1120-1128*

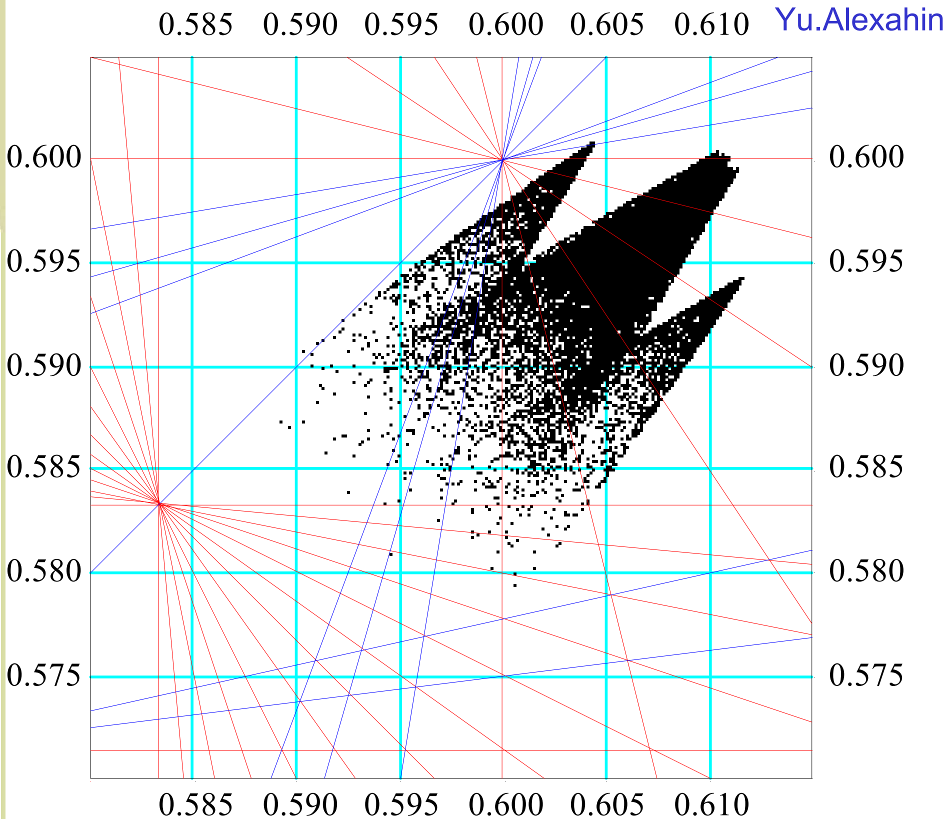
** *average in stores #1832-1845*

\# *average in stores #2114-2153 (9 stores)*

\#\# *average in stores #2315-2361*

Beam-Beam Effects in Collisions

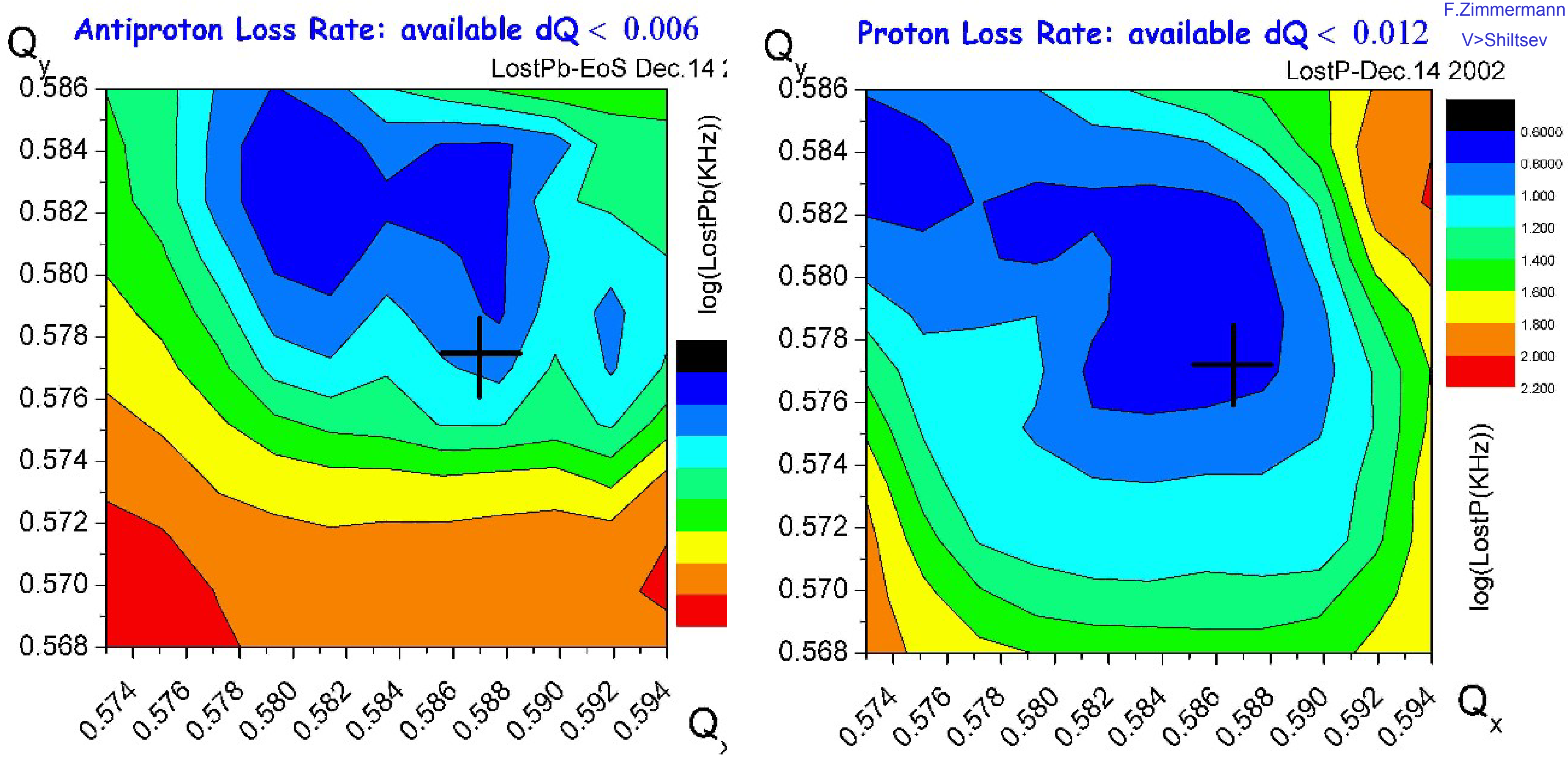




- pbar bunches near abort gaps have better emittances and live longer
- emittances of other bunches are being blown up to 40% over the first 2 hours – see scallops over the bunch trains (small anti-scallops for protons)
- the effect is (and should be) tune dependent - see on the right
- recently, serious effects of pbars on protons – completely unexpected

Beam-Beam Effects: Losses @ HEP

XL.Zhang, M.Xiao
K.Bishoberger,
F.Zimmermann
V>Shiltsev



- At the beginning of the store available WP area is even smaller dQ < 0.004 … and this is at N_p=180e9
- No available tune WP space expected above 240e9

How to Deal with Beam-Beam?

- On-going activities:
  - "Better"(~larger) beam separation
    - open aperture, optics, add/improve separators
    - against Long-range BB
  - Beam-Beam Compensation with electron lenses
    - provide variable tune shifts and tune spread in bunches
    - against Long-range and Head-On BB
- Under consideration:
  - Add 6 proton bunches → 42x36 scenario
    - against Long-range BB in collisions
    - make worse at 150 GeV, ramp, squeeze; faster kicker
  - Wire Compensation
    - against Long-range BB

Wire Compensation

- Just started (after DoE Review Nov'02)
  - resonance strength analysis (T.Sen, B.Erdelyi)
  - practical considerations (T.Sen, V.Shiltsev)
- So far wires look challenging but promising
  - Scale of the problem:

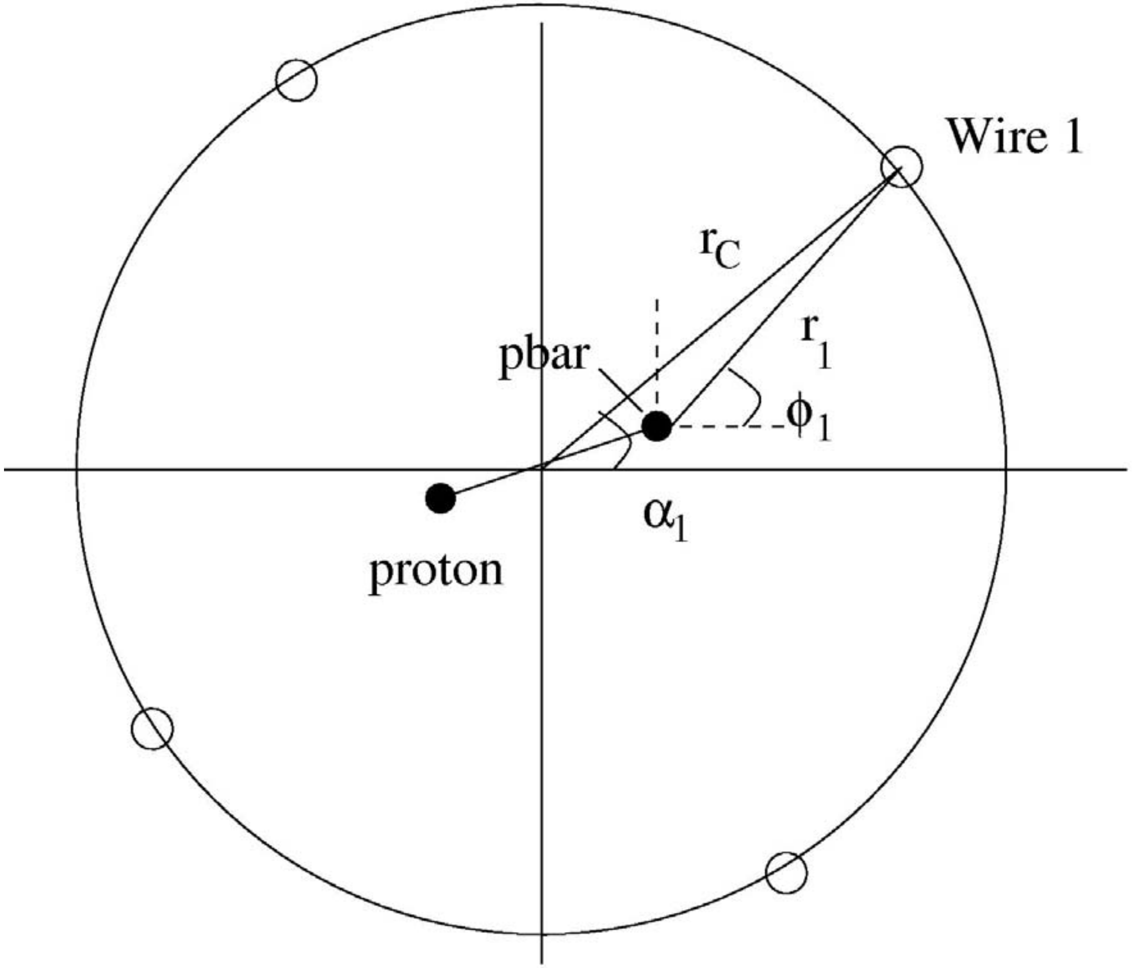
$$J_w * L_w = 2 * e * c * N_p(total)/N_{wires}$$

  - That gives 232A*m for N_p=9720e9 and N_wires=4
  - Wires to be withing 10 mm from pbars
  - Not in a single location (~4), some preferred
  - ~(4-7) wires at each location (to compensate relevant resonances)
- Plan: continue theory studies → start design

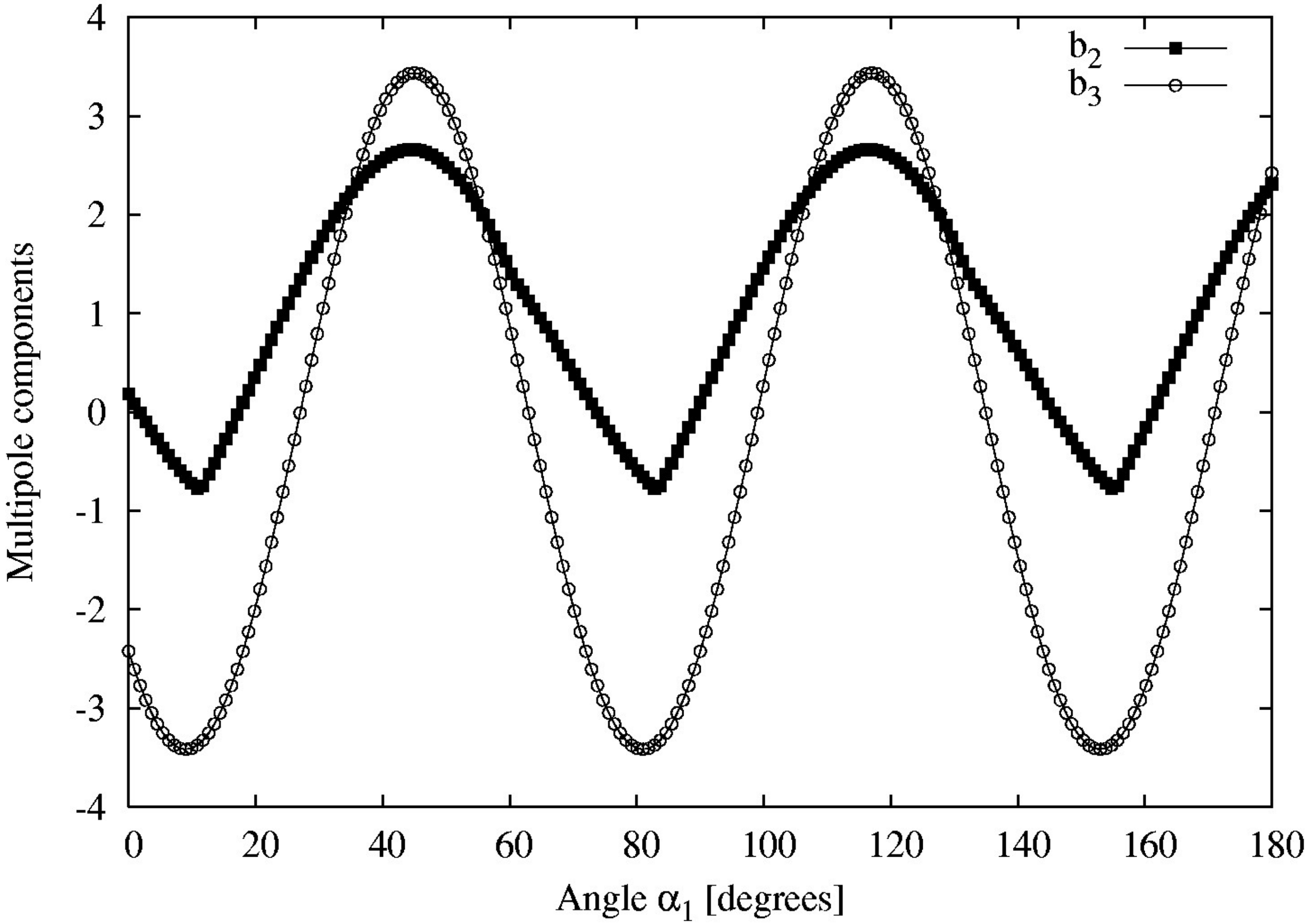
Wire Compensation - I

T.Sen

B.Erdelyi



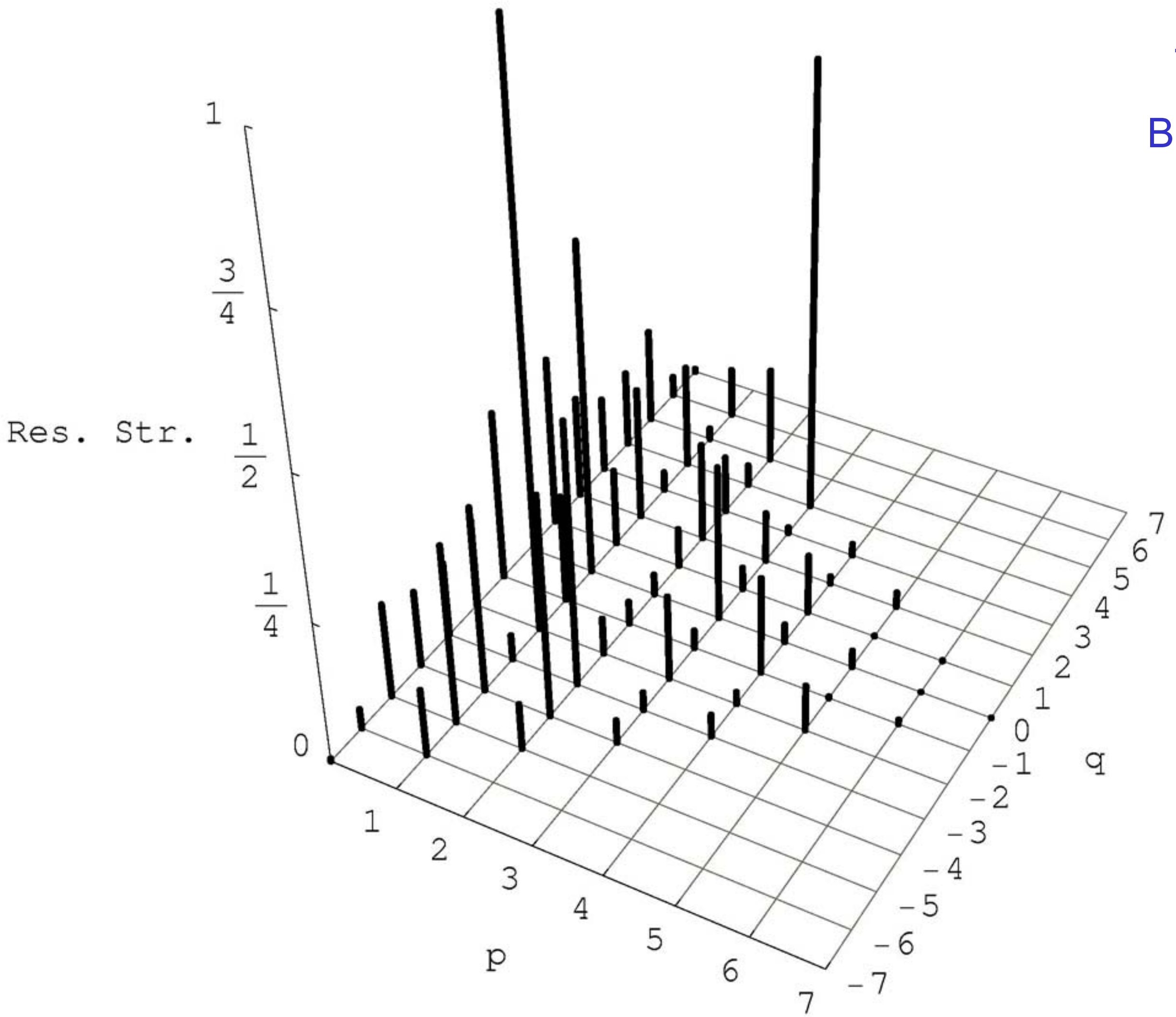
Wire Compensation - II



T.Sen

B.Erdelyi

Wire Compensation - III

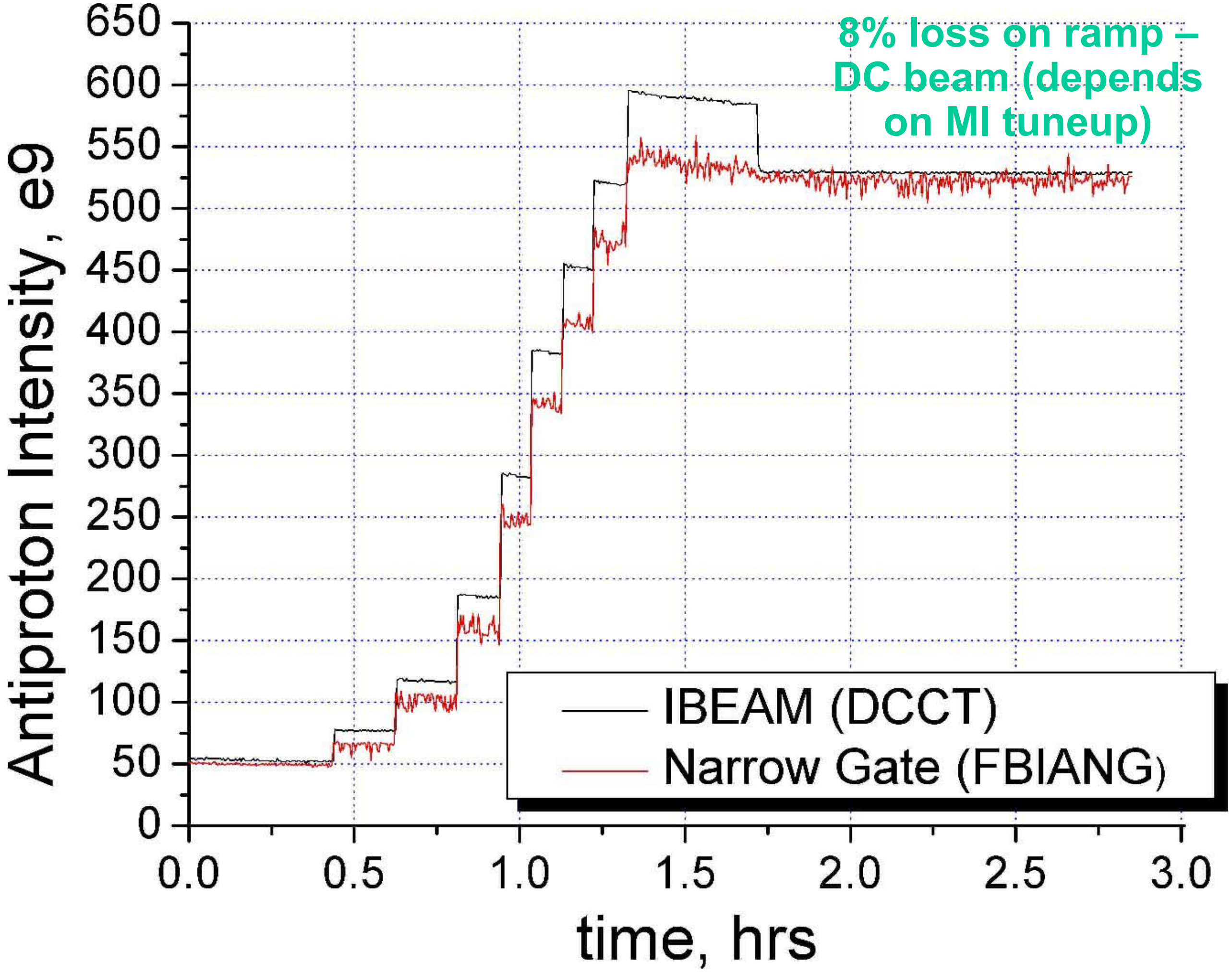


T.Sen

B.Erdelyi

Beam-Beam Effects: Pbar Only

Antiproton Only Store: 1% loss on ramp, τ_{150}=20 hrs, τ_{980}=160 hrs

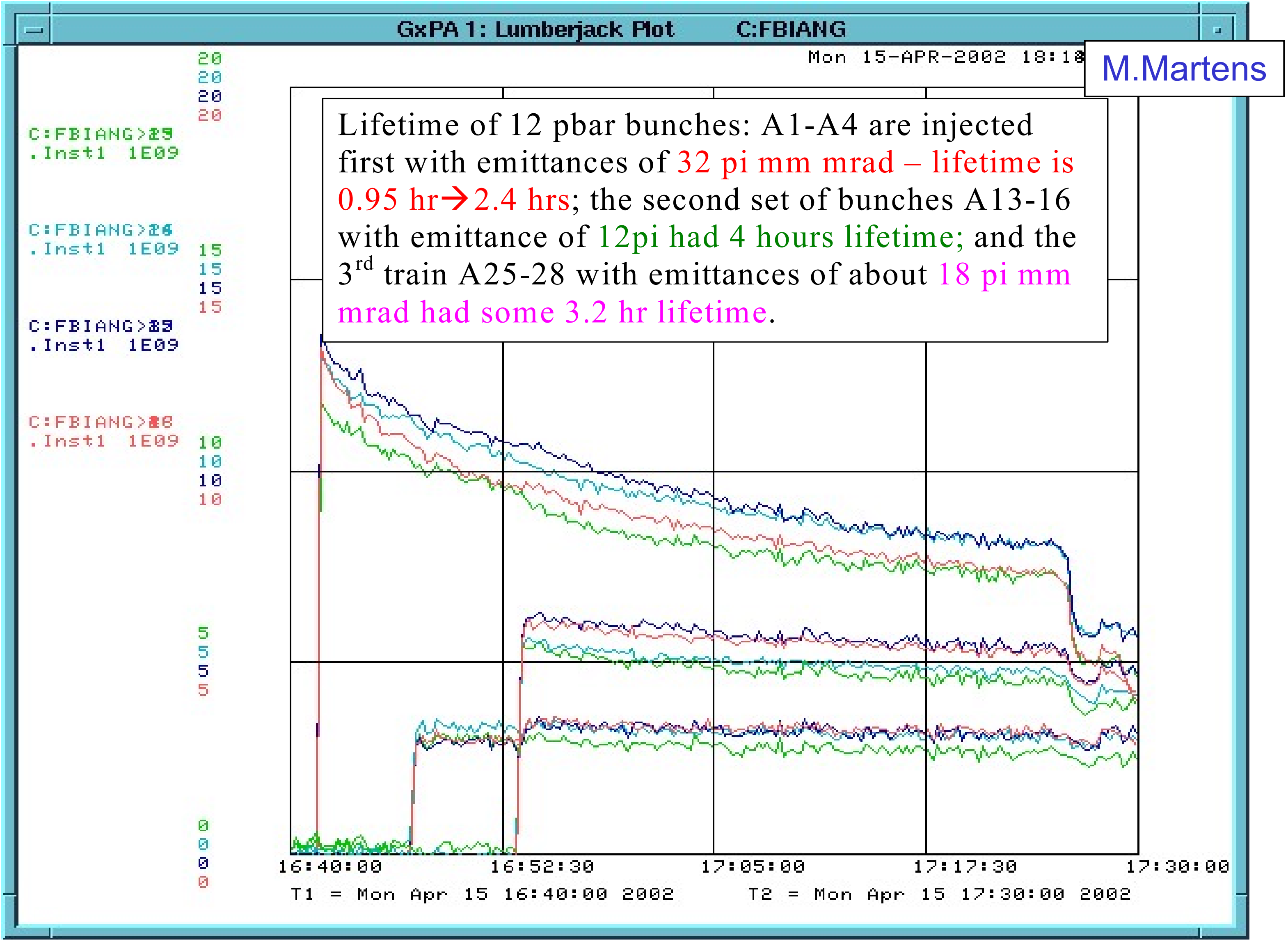


Beam-Beam Effects: Antiprotons Suffer

Store	*N_p, e9*	*Out of AA, mA*	*Loss at 150*	*Loss on ramp*	*Loss in squeeze*	*Pbars at low-beta*	*L, e30*
Mar'02	5100	90	20%	14%	22%	251	9.4
1303	6070	103	16.4%	11.6%	3%	476	19.5
1289	6990	105	18%	20%	11%	387	19.6
Oct'02	6430	132	9%	8.3%	5%	790	32.4

- Pbar intensity lifetime at low-beta is 15 to 50 hrs (50-70 due to luminosity)
- Pbar emittance lifetime at low-beta is 10 to 40 hrs
- Some effects are seen in protons (see below)

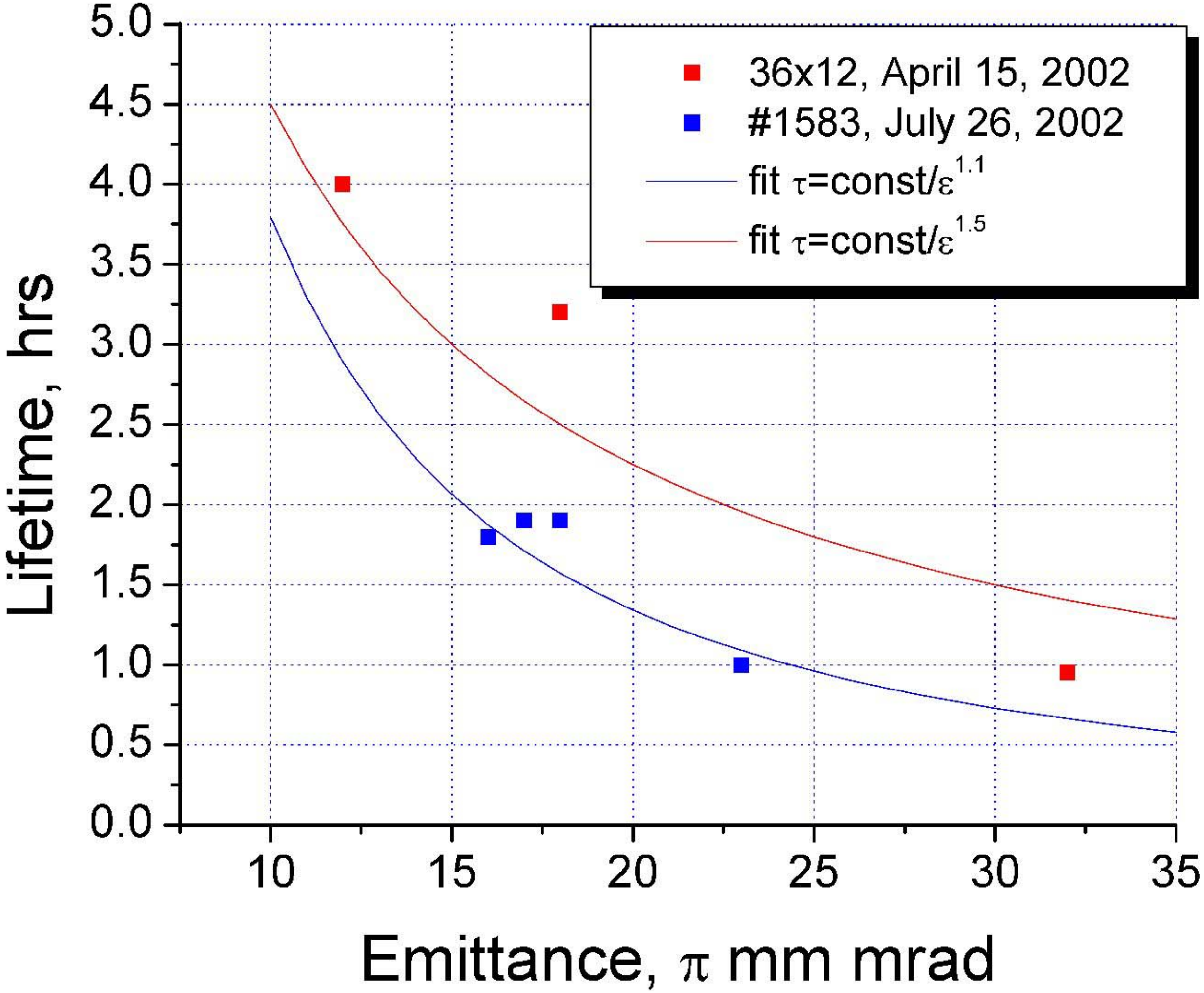
Beam-Beam @ Injection vs Emittance



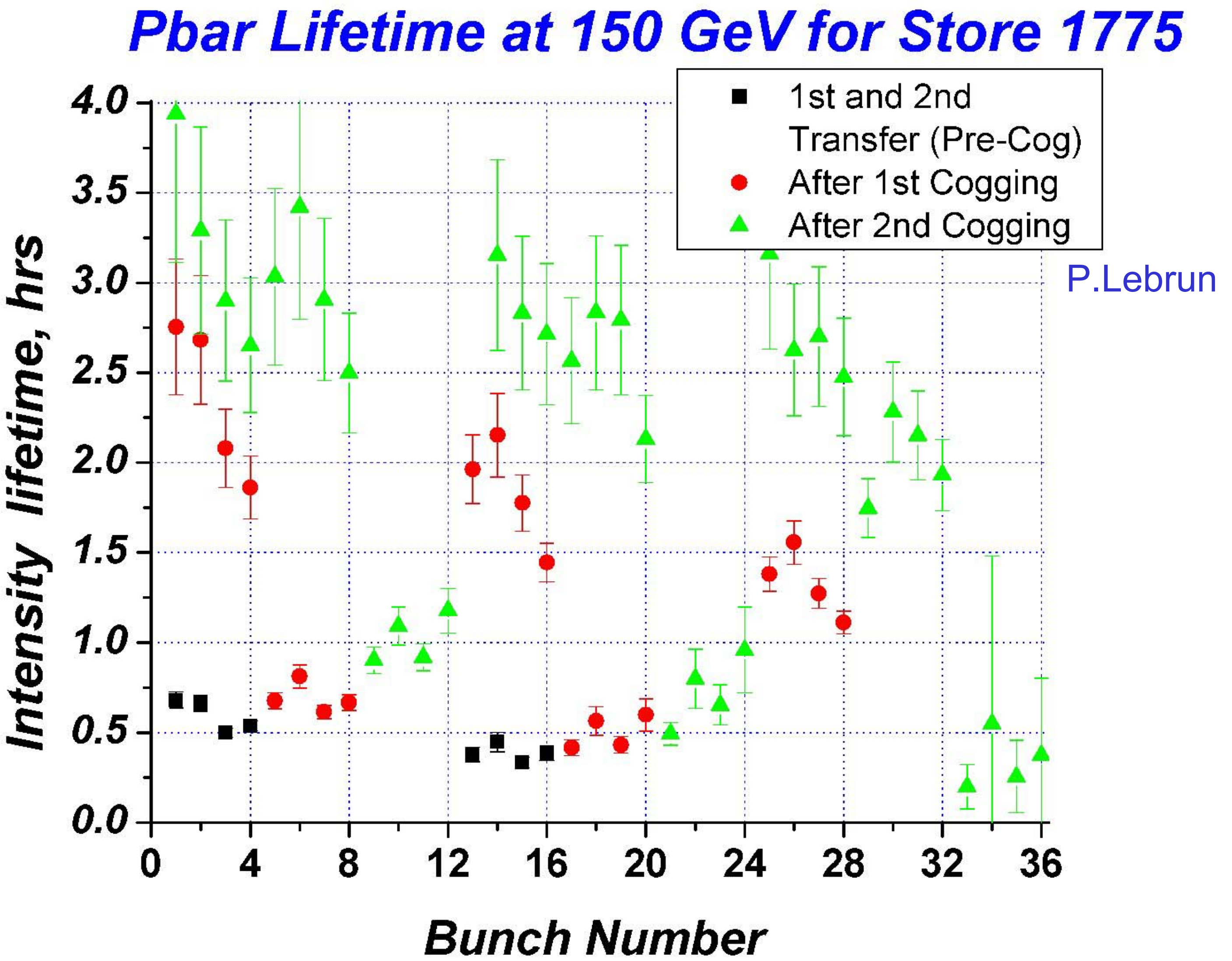
Lifetime of 12 pbar bunches: A1-A4 are injected first with emittances of 32 pi mm mrad – lifetime is 0.95 hr→2.4 hrs; the second set of bunches A13-16 with emittance of 12pi had 4 hours lifetime; and the 3rd train A25-28 with emittances of about 18 pi mm mrad had some 3.2 hr lifetime.

Beam-Beam @ Injection vs Emittance

Pbar lifetime vs emittance at injection scales as $1/\varepsilon^{(1.1-1.5)}=1/A^{(2.2\text{-}3)}$



Beam-Beam @ Injection: Bunch-by-Bunch

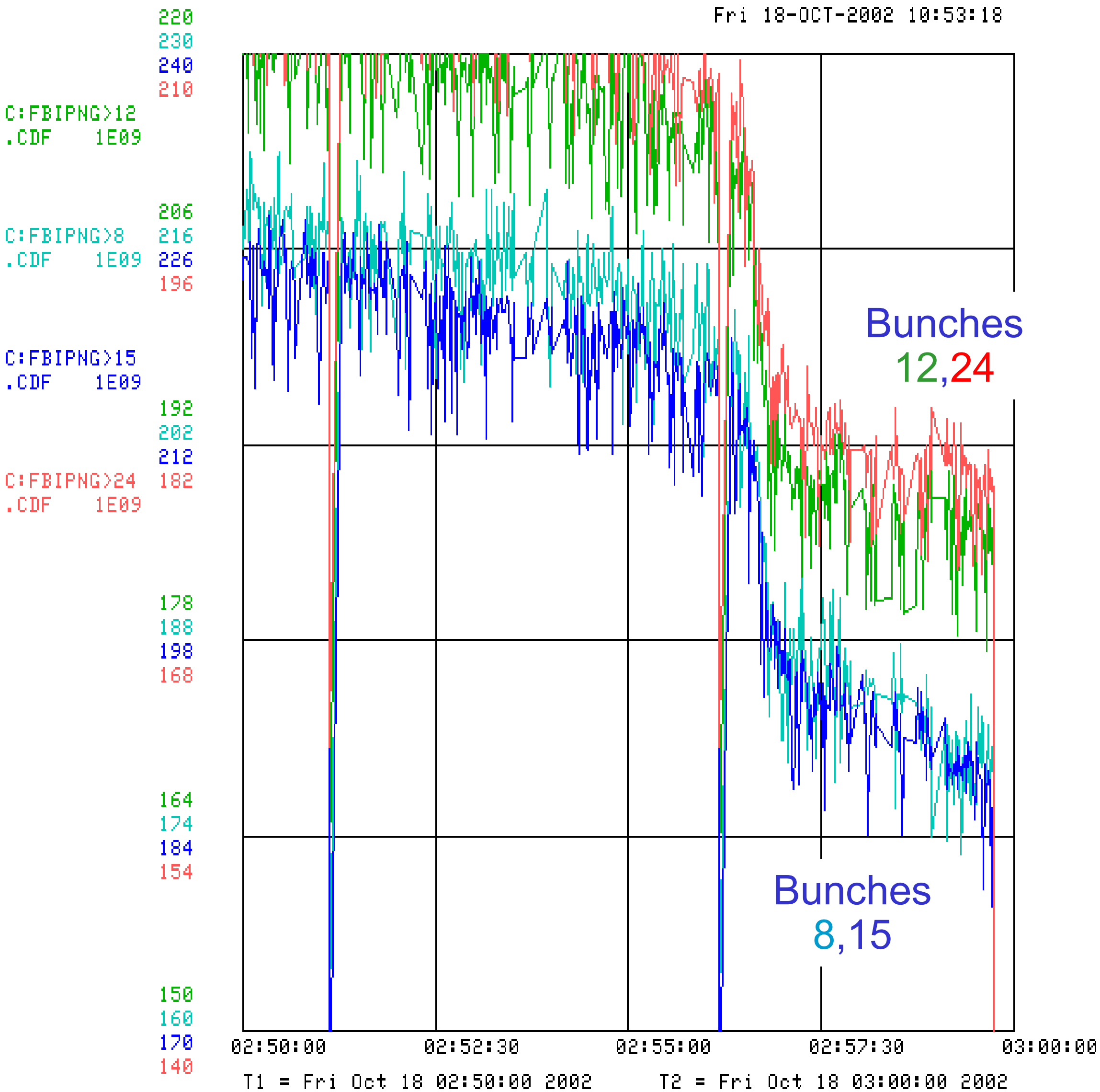


Beam-Beam Effects at 980 GeV

- Suffered 10-20% pbar loss during squeeze
  - During transition from injection to collision helix
  - Minimum beam separation was only ~1.8σ
  - New helix increased min beam separation to ~3σ
  - Pbar loss during essentially eliminated

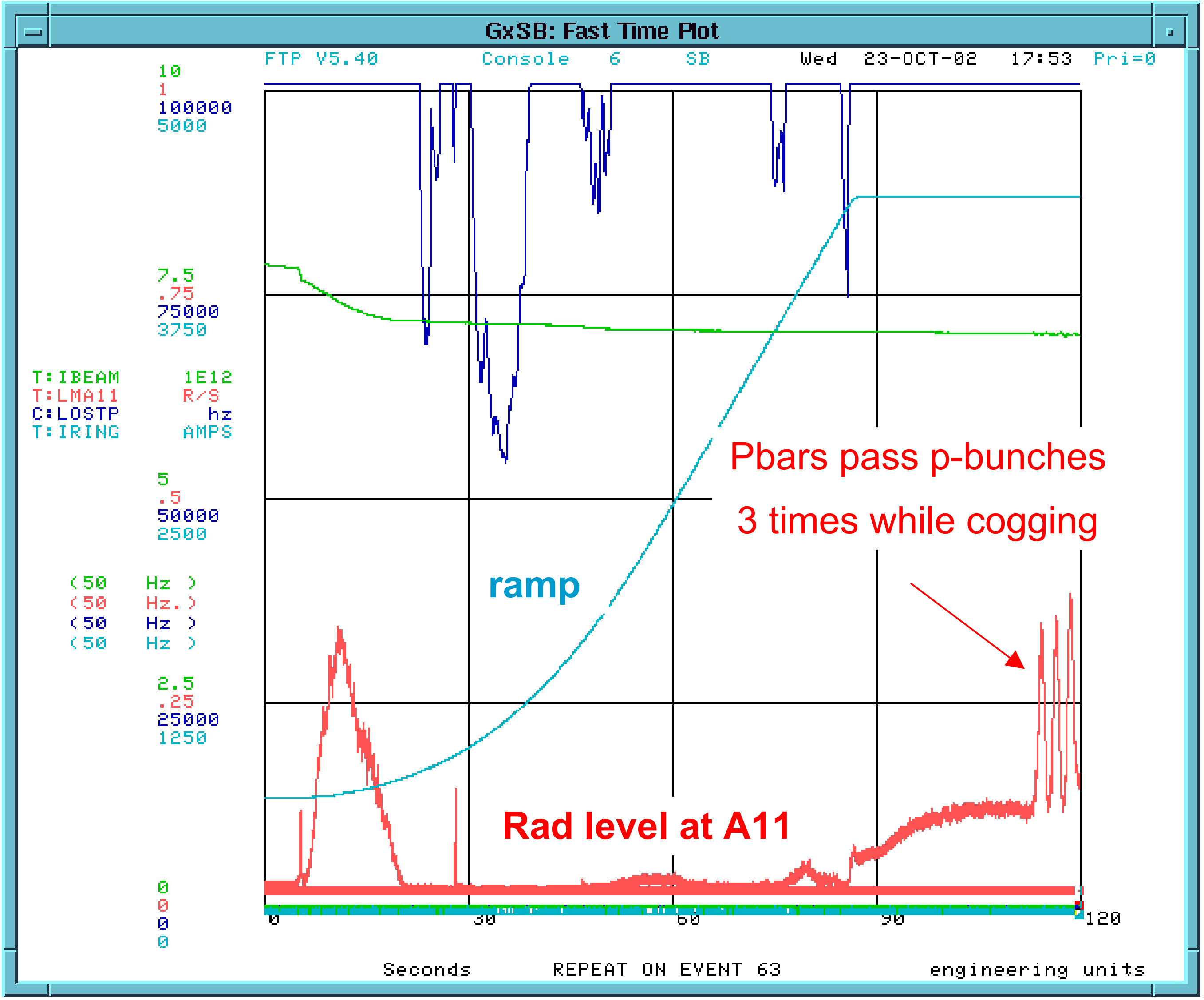
- ☹ lifetime ≈ 9-10 hrs in first two hours of store
  - Increase helix separation to reduce long-range beam-beam effects? (72 "parasitic" crossings)
  - Pbar tune shift depends position in train ⇒ optimize tunes for most bunches
  - Use electron lens to compensate pbar tune shifts

Beam-Beam Effects in Protons

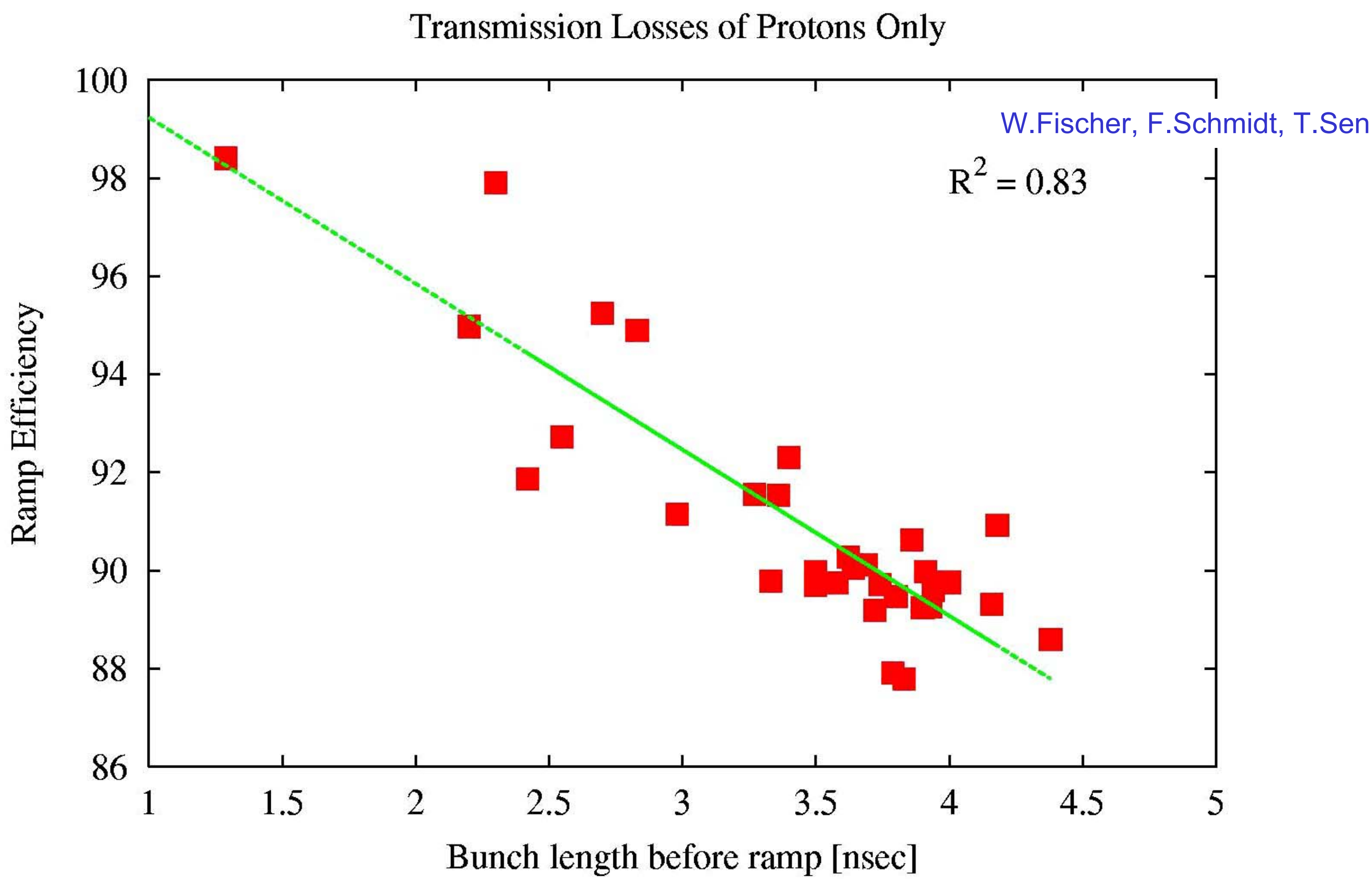


- See losses in squeeze in store #1868
  - Losses of bunches #12,24,36 were small (1e9/min)
  - All other bunches lost intensity very fast (4e9/min)
  - That resulted in quench at A11
- We have small “anti-scallop” (“smile”) effect in proton emittances at HEP
  - Bunches #1,12,13,24,25,36 have 1-2 pi larger emittances than others after being 1-few hours in collisions
  - Their intensity lifetime is smaller, too
- Antiprotons also help to make protonbeam more stable on ramp and squeese
  - Proton instability is rarely observed in 36x36 stores compared to the same intensity 36x0 stores
  - Tune spread due to pbars is about (few)e-4

Proton Losses While Cogging Pbars

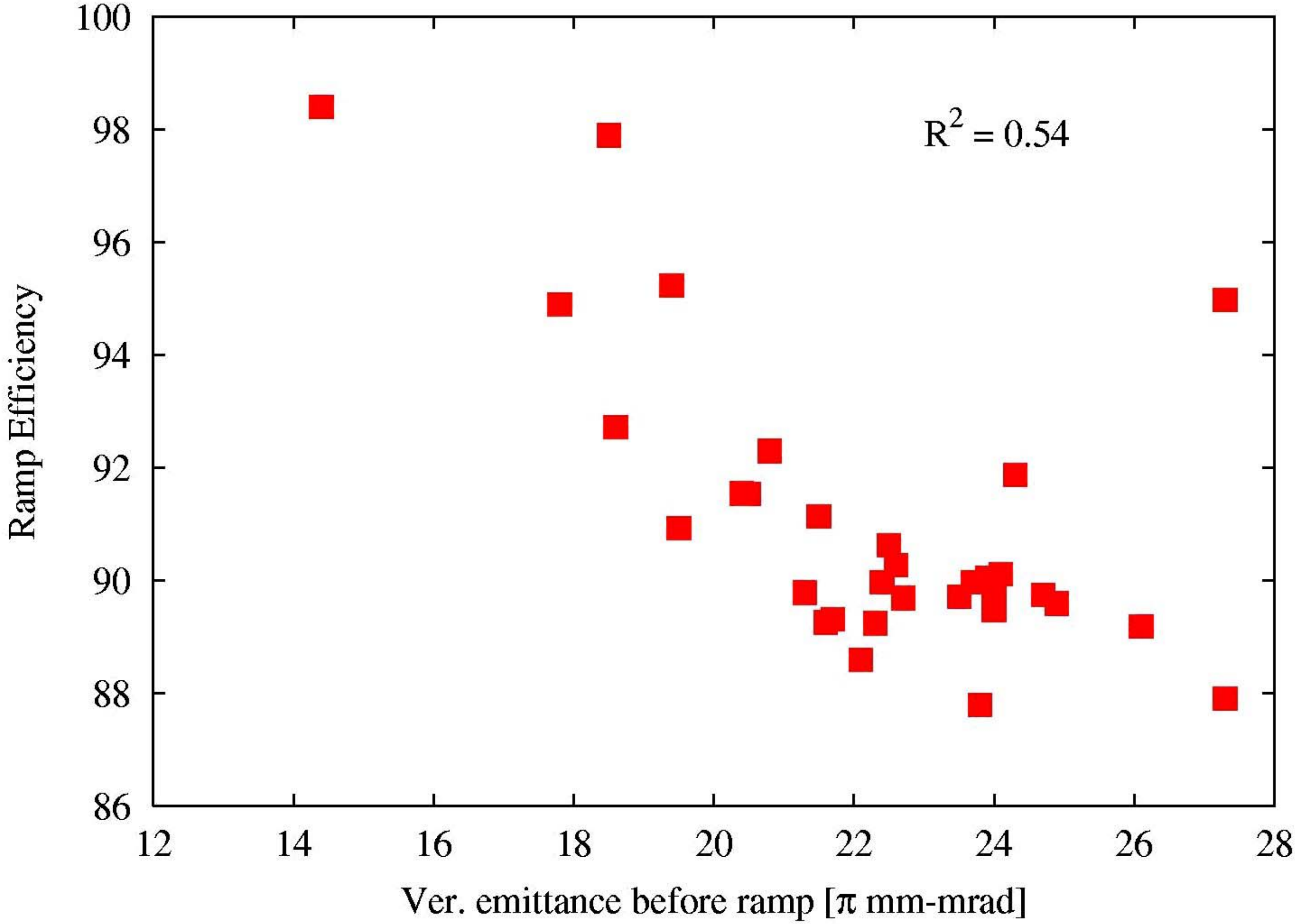


Proton Loss on Ramp



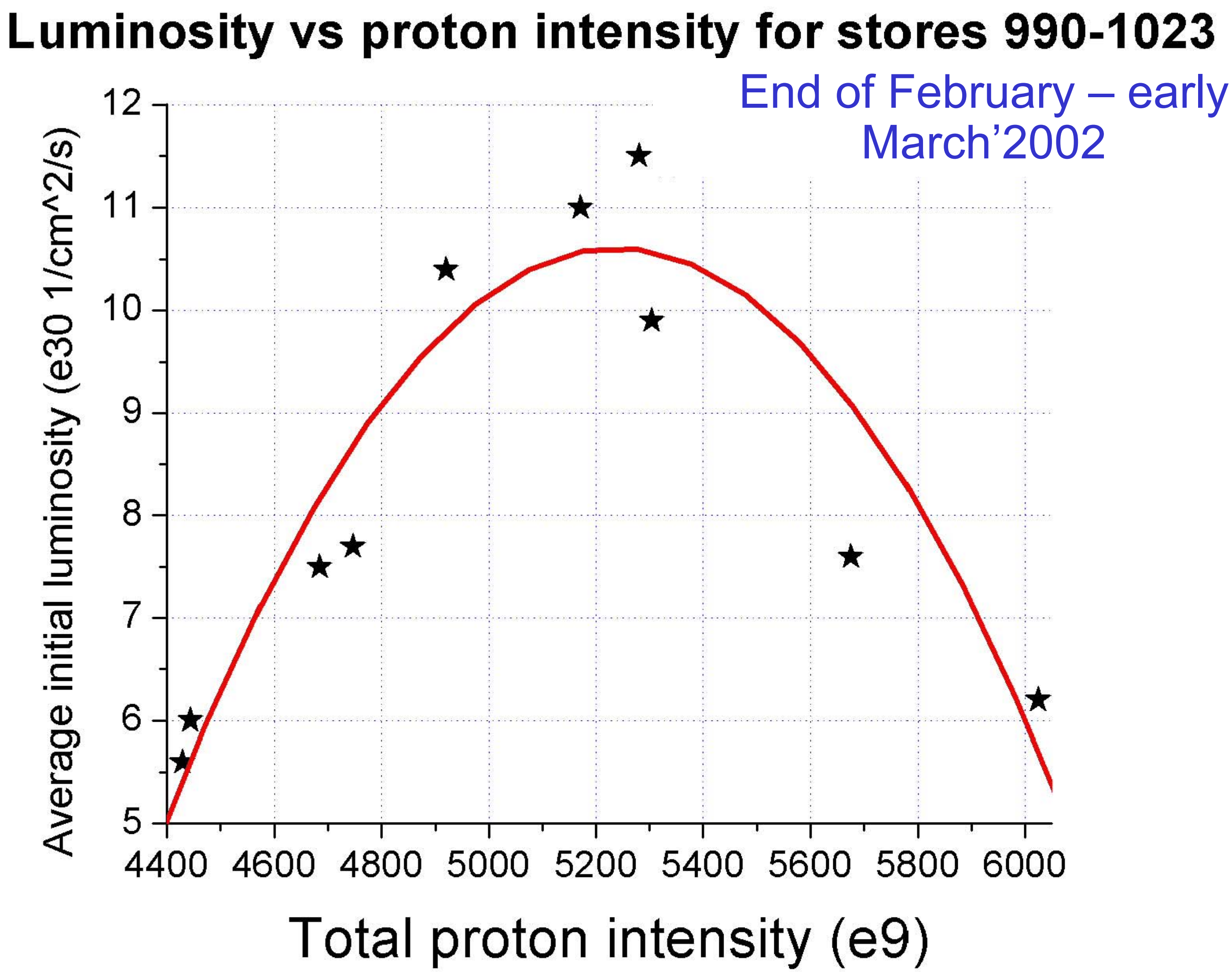
- ramp efficiency also anticorrelates with N_p, vertical emittance and Dl-emittance

Proton Loss on Ramp vs Emittance

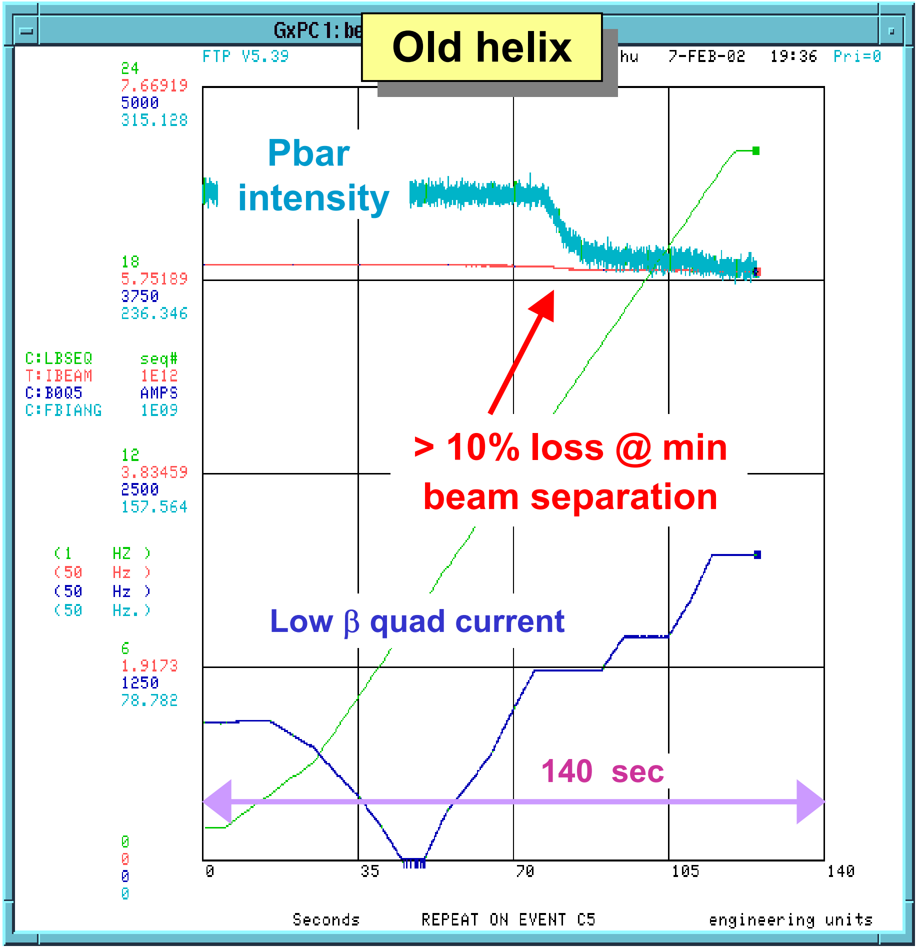


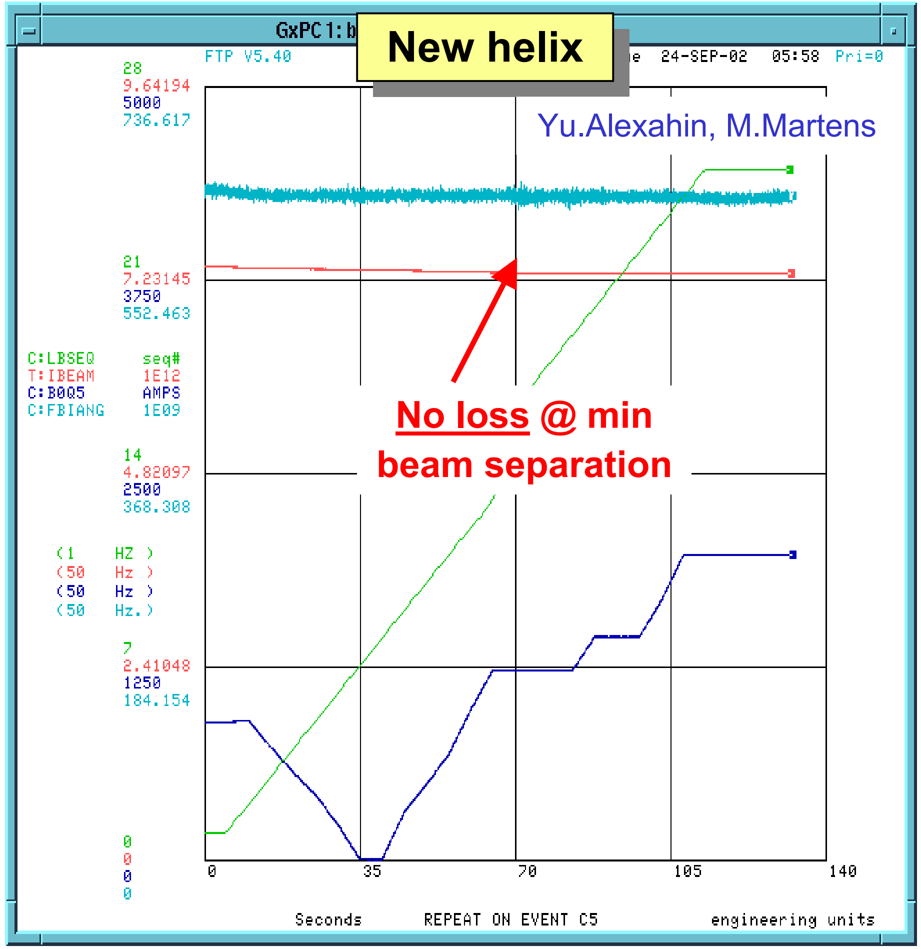
W.Fischer,
F.Schmidt,
T.Sen

"Sequence 13" Affects Luminosity



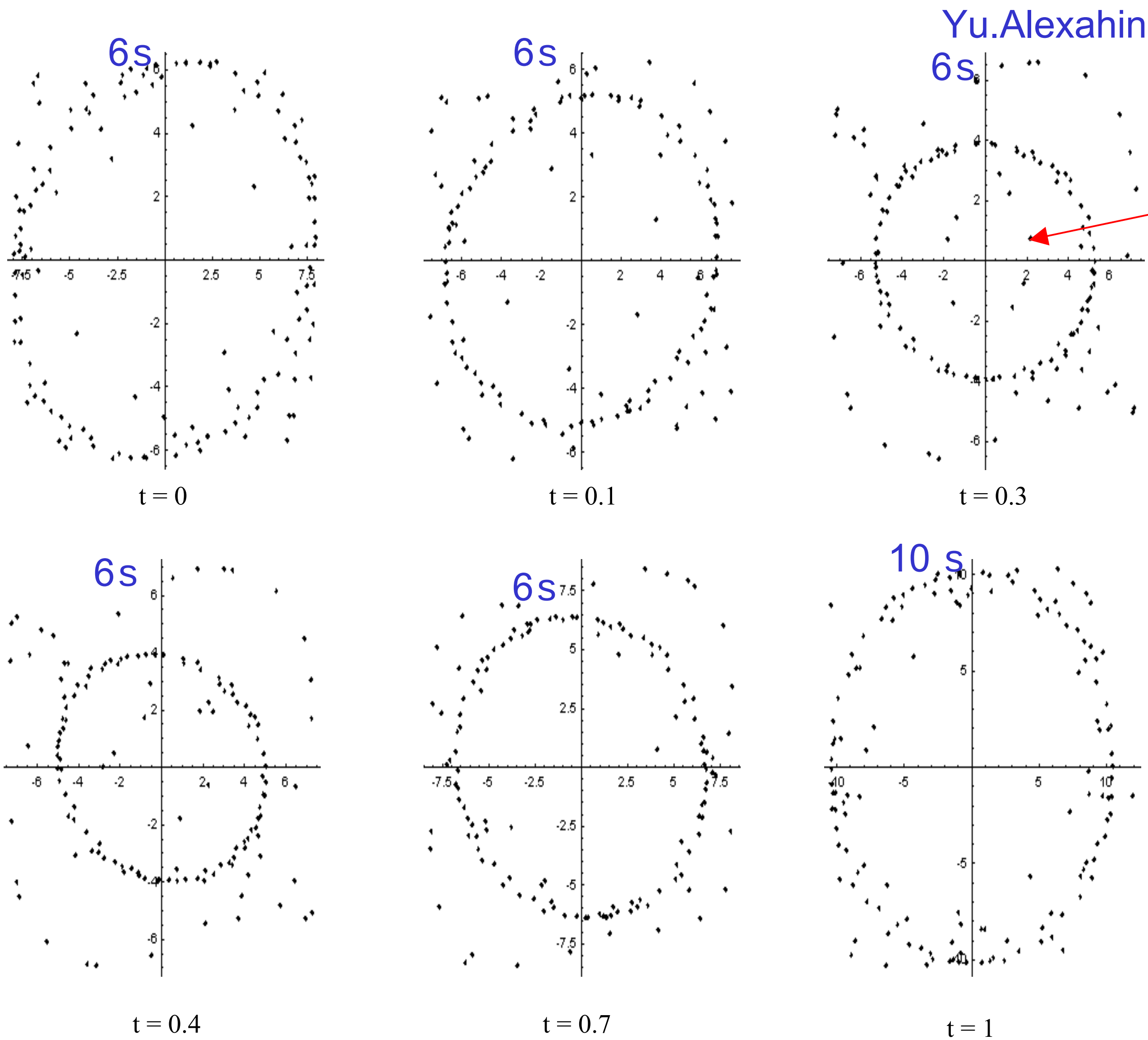
Pbar Loss During Squeeze ("Sequence 13")





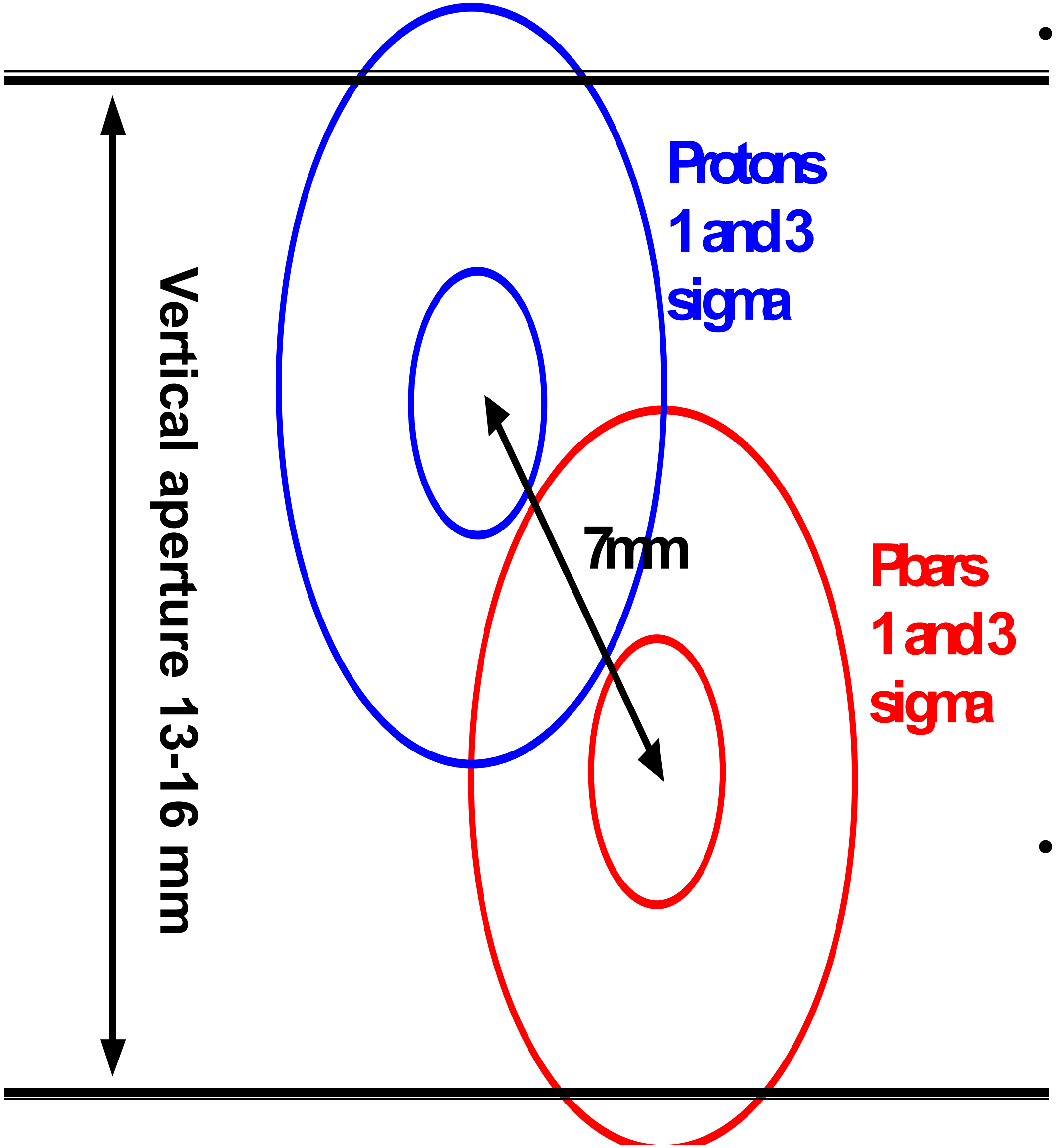
- Suffered 10-20% pbar loss during squeeze
  - During transition from injection to collision helix
  - Minimum beam separation was only ~1.8σ
  - New helix increased min beam separation to ~3σ, loss essentially eliminated

Beam-Beam Effects in Squeeze



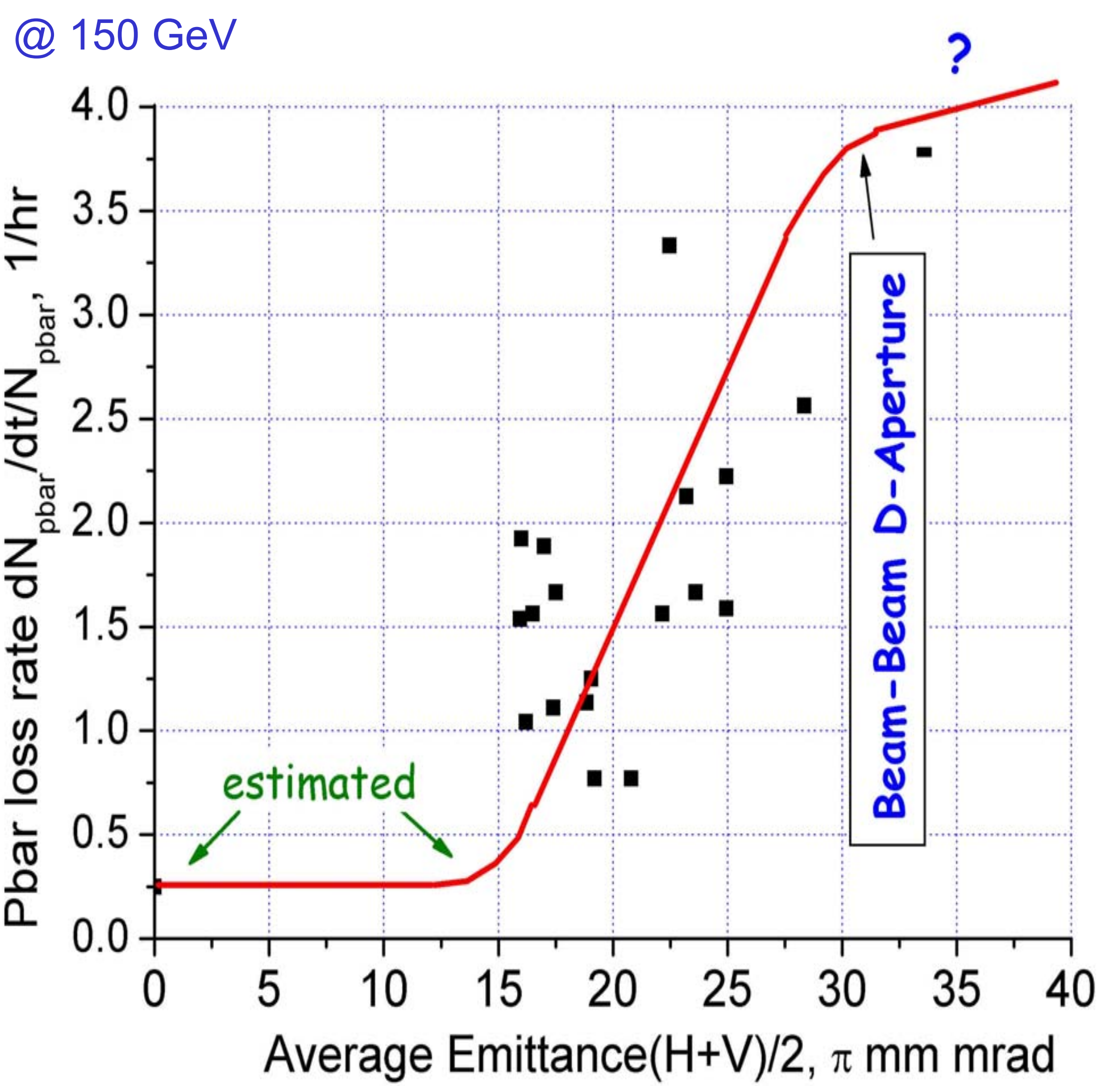
- Minimum beam-beam separation turned out to be only **1.8σ**
- Normalized separations $\Delta x/\sigma_x$, $\Delta y/\sigma_y$ at all possible IPs with 36×36 collision cogging in sigma's for the reference emittance ε_n=15π mm·mrad. t = 0 – seq13, t = 1 – seq14 (see plots)
- The separation has been increased to 2.7σ by adding 2 more breakpoints, also speed of the squeeze doubled there and the loss gone
- Lesson – only minimum separation matters

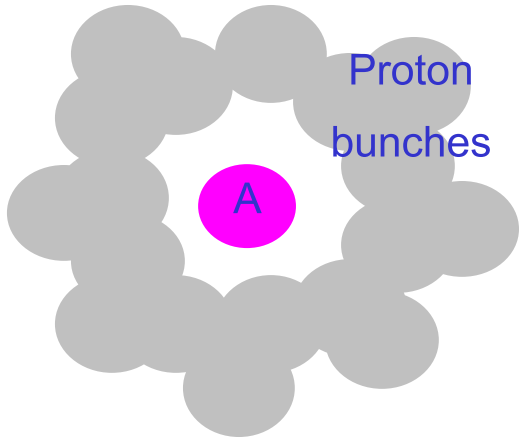
Lifetime Issues at 150 GeV



- LR beam-beam effects poor pbar lifetime 0.3-1 hr
  - Pbar lifetime depends on emittances, N_p and bunch number
  - Original injection helix has been modified, separation increased and optimized to fit tight C0 aperture (“new-new helix”)
  - Replace lambertsons @ C0 – gain 25 mm vertically
  - Modify high β section at A0 formerly used for fixed-target extraction
- Poor proton lifetime on helix ~ 2 hr
  - depends on chromaticity
  - Instability prevents lower chromaticity (now 8)

Proton Beam as "Soft Donut Collimator"





•pbar losses strongly depend on pbar emittances and N_p

• measures taken to reduce emittances:

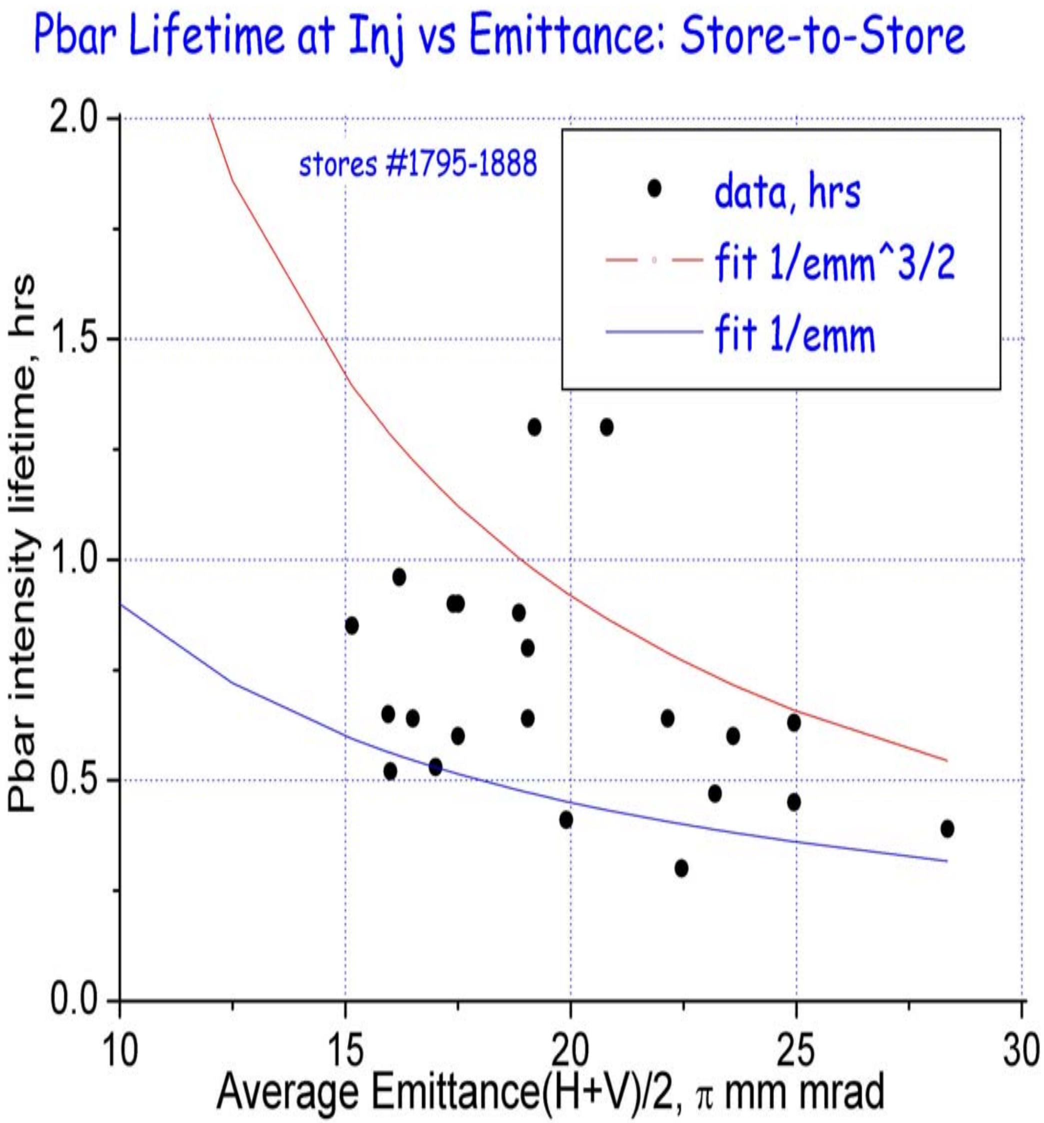
- AA "shot lattice"

- fix injection errors (BLT)

- match injection lines

- tuneup injection kickers

Pbar Losses vs Emittance/Helix Size



- expected $t \partial A^{(2-3)}$
- next steps – to increase beam-beam separation (helix size):

\- C0 aperture: ~30% in A @150

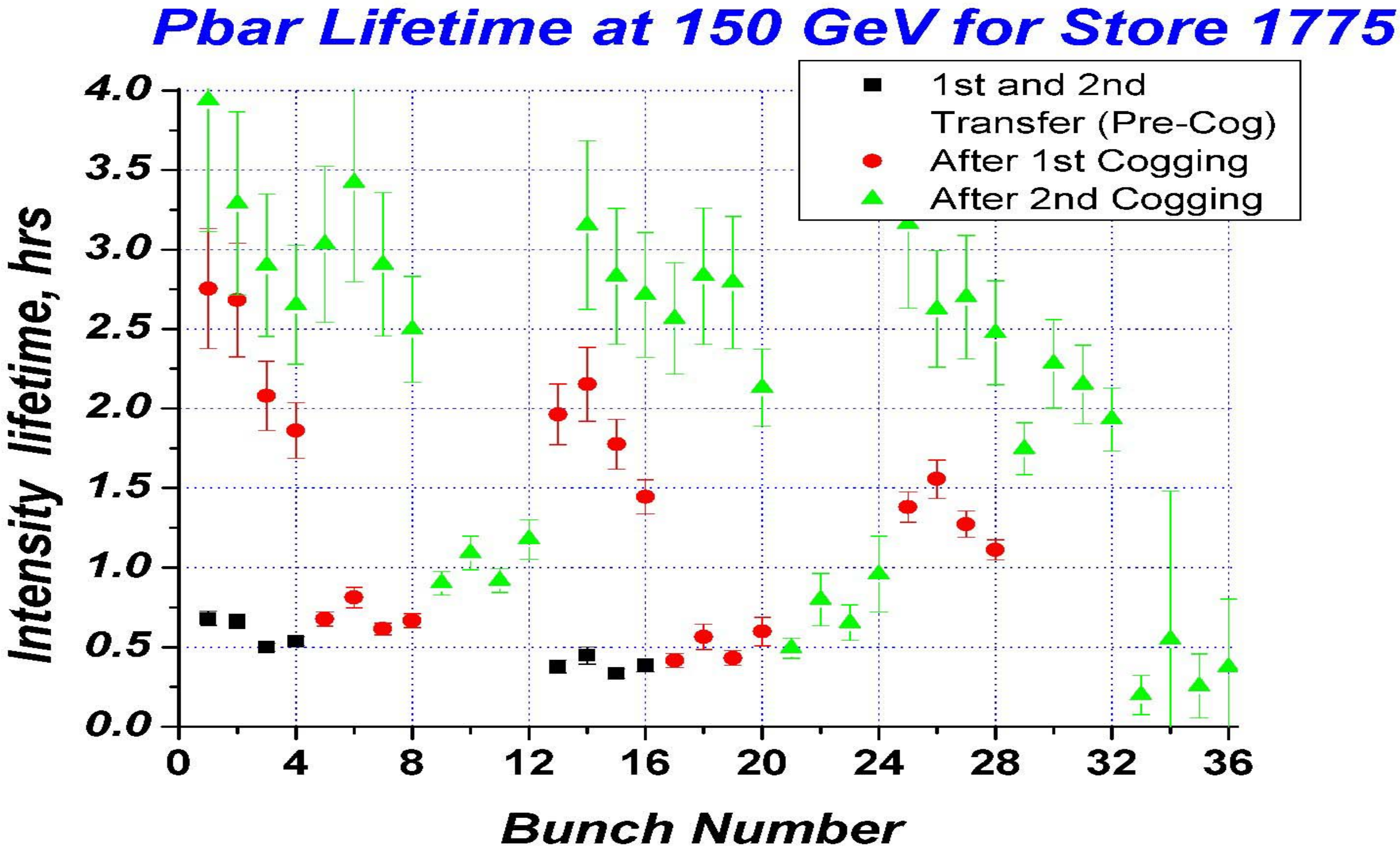
–Replace lambertsons @ C0 – gain 25 mm vertically

– that will allow some 30% larger sepration around the ring until the next aperture restriction (F0, A0, B0, D0, E0)

\- A0 lattice: ~16%? in A @150&LB

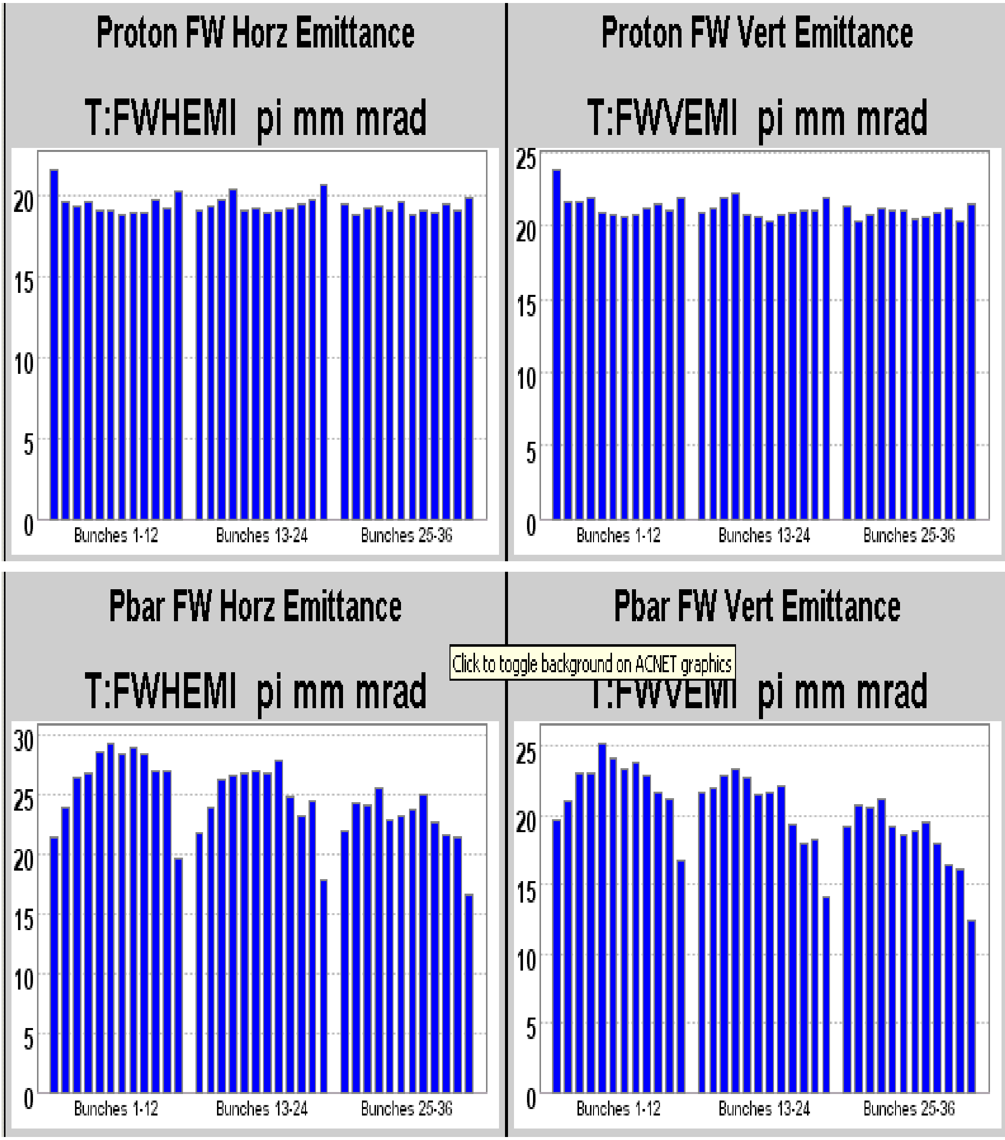
–Modify high β section at A0 formerly used for fixed-target extraction

Beam-Beam Effects Now: Injection



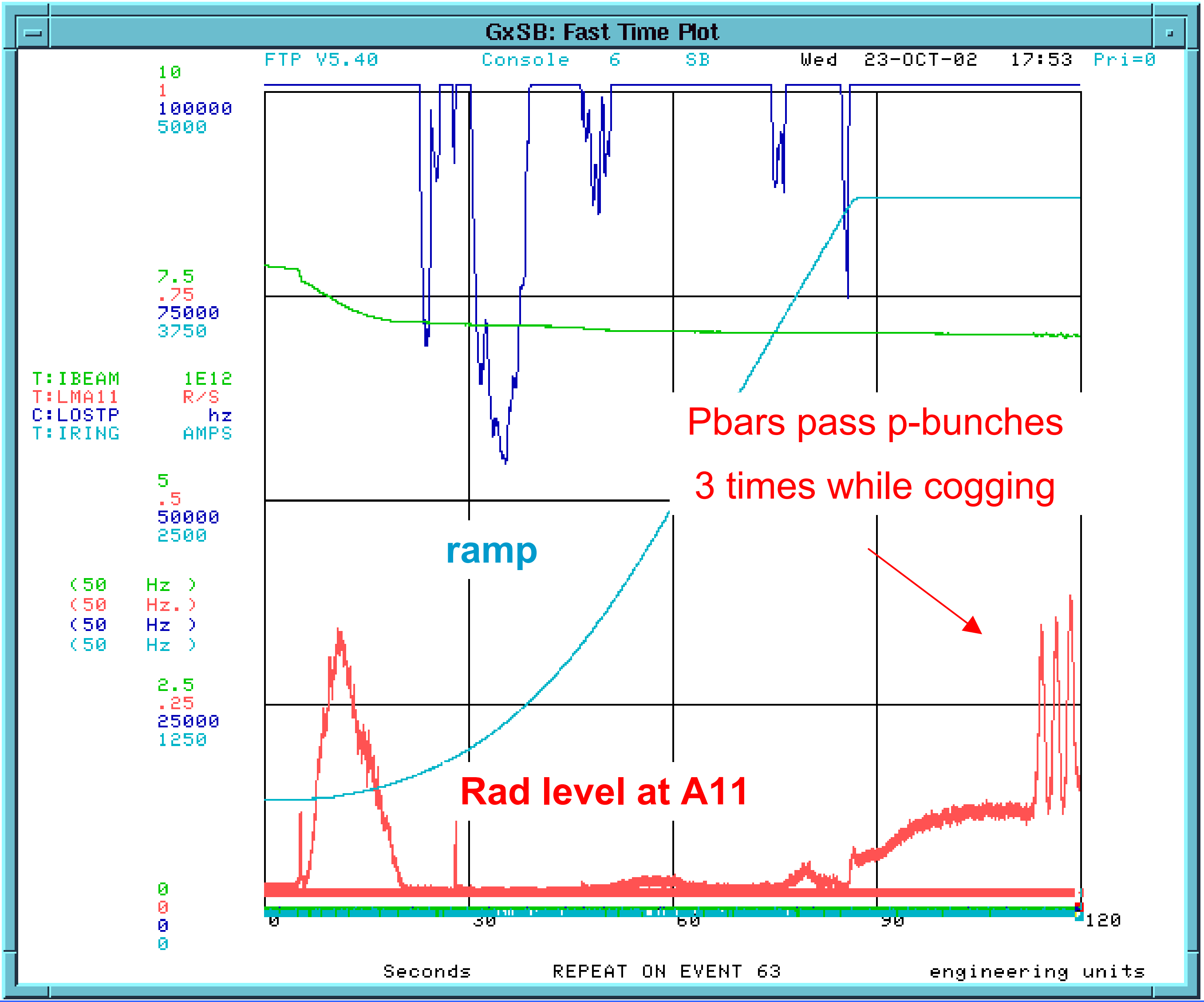
- Loss depends on N_p, separation, aperture, emittances, dp/p, tunes and C_v,h
- Scaling not determined yet – to be done ASAP

Beam-Beam: Bunch-by-Bunch

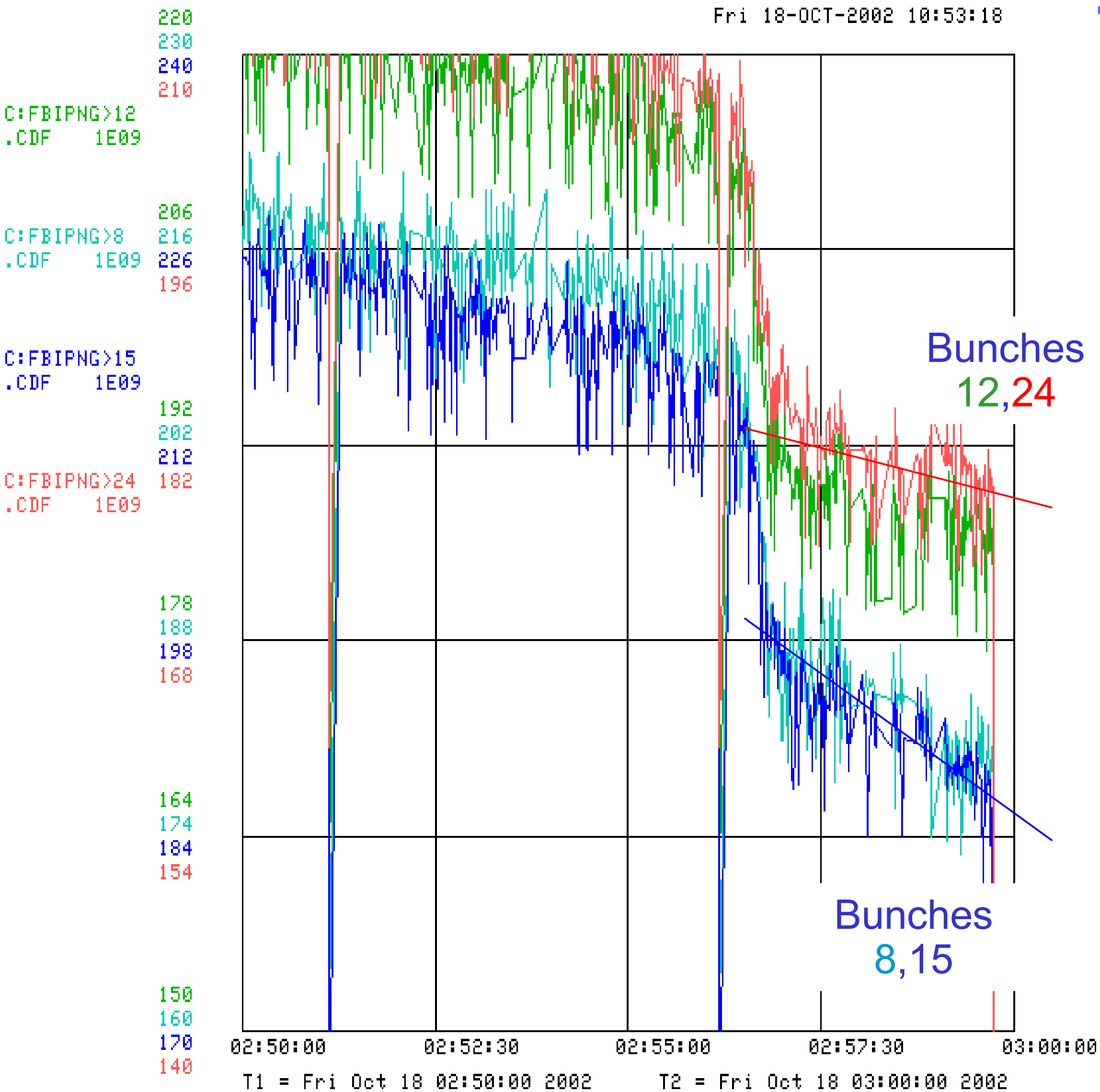


- "Scallop" profile of bunch emittances
- At the beginning of the store

Proton Losses While Cogging Pbars



Beam-Beam Effects in Protons



See losses in squeeze in store #1868

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- That resulted in quench at A11

We have small "anti-scallop" ("smile") effect in proton emittances at HEP

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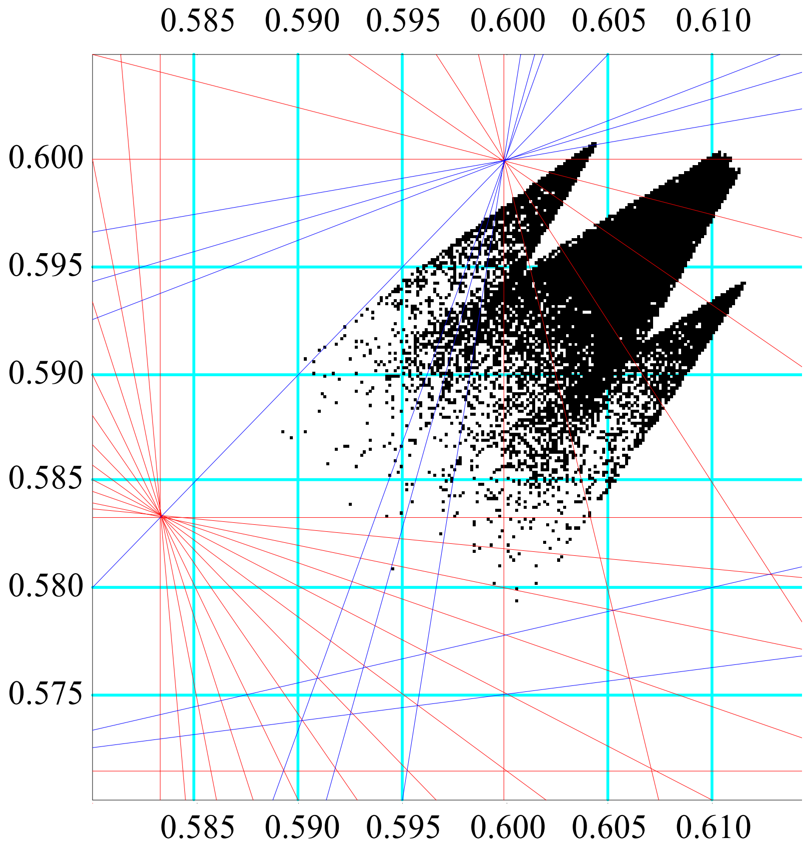
- Their intensity lifetime is smaller, too

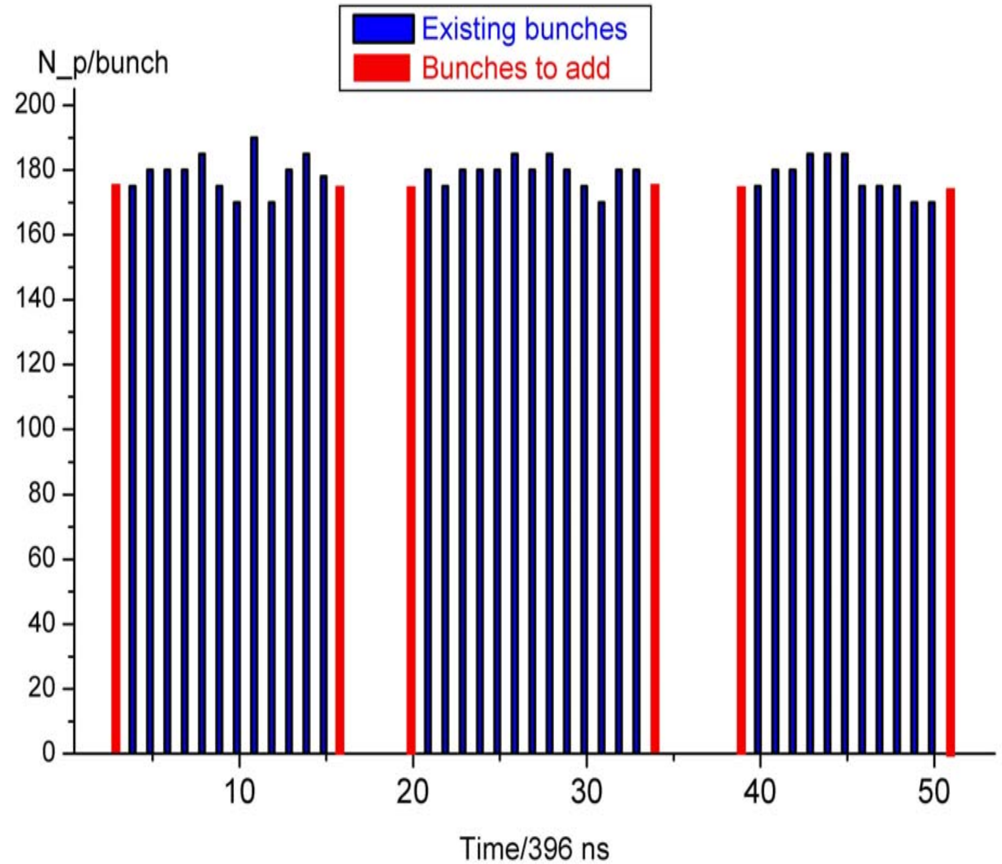
Antiprotons also help to make protonbeam more stable on ramp and squeese

- Proton instability is rarely observed in 36x36 stores compared to the same intensity 36x0 stores
- Tune spread due to pbars is about (few)e-4

Add 6 Proton Bunches

Yu.Alexahin





- Will help at HEP only – reduce pbar bunch tune spread
- Will make beam-beam worse at 150 GeV, ramp, squeeze; faster kicker
- Plan: consider details and, perhaps, perform beam studies

Lifetime vs WP with dQ_{TEL}~0.004